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A LIGHTNING SUMMARY AND DECISION MODEL FOR THUNDERSTORM PREDICTION AT WHITEMAN AIR FORCE BASE, MISSOURI

A Thesis

by

RANDALL GERALD BASS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 1996

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ABSTRACT

A Lightning Summary and Decision Model for Thunderstorm Prediction at Whiteman Air Force Base, Missouri. (August 1996)

Randall Gerald Bass, B.S., North Carolina State University

Chair of Advisory Committee: Dr. Richard E. Orville

A cloud-to-ground lightning summary was developed for a 139x185 kilometer area centered at Whiteman Air Force Base. Spatial and temporal patterns, and first stroke peak currents were analyzed from 1989-1995. Stability indices were examined for thunderstorm and non-thunderstorm periods on a seasonal basis. Regression equations developed using these variables distinguished thunderstorm periods from non-thunderstorm periods. Decision models were presented that combined responses from the equations with other meteorological considerations.

A preferred track for springtime thunderstorms was located between the base and the Ozark Mountains. No preferred track was found during the other seasons.

Although diurnal distributions of lightning flashes showed that thunderstorms were possible at any time, late afternoon and nocturnal maxima were observed during the spring and summer. The nocturnal maximum disappeared during the fall. First flash times for thunderstorm events were spread out for the spring and fall. A summertime peak between 1800-2100 UTC (1200-1500 CST) was detected. Last flash times tended to be random, but preferences were observed for early evening and early morning.

The percentage of positive flashes nearly doubled in 1994 and 1995 compared to previous years. An increase was observed in the number of positive flashes with peak currents below 60 kA. An increase of negative flashes with peak currents below 20 kA was seen, but contamination by intracloud flashes could not be disregarded.

The four spring and fall regression equations for thunderstorm prediction performed better than the two for summer. When tested on independent data, one spring equation had a critical success index (CSI) of 59% and probability of detection (POD) of 100%. One summer equation had a CSI of 55% and POD of 85%.

Two thunderstorm decision models were constructed using the seasonal regression equations and several meteorological conditions such as frontal system location. Skill scores for these models were higher than those for any individual equation. The spring model performed best with a CSI of 79% and POD of 100%.

DEDICATION

This manuscript is dedicated to my lovely wife Amy and beautiful daughter Briana. Their love, support, and encouragement during this endeavor helped carry me through the times when I thought I'd never finish. I also want to thank them for their patience with me, especially the last few months before completion.

Most of all, I want to thank Amy for being my wife, and my best friend, these last seven years. We've been able to overcome all obstacles together, many of which I could not have conquered alone. I love her with all my heart.

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I would like to take this opportunity to thank the members of my committee, Dr. Richard E. Orville, Dr. Dusan Djuric, and Dr. H. Del Var Petersen for their help and guidance during my research. I especially thank Dr. Orville for chairing my committee and for his support, help, and suggestions in focusing my research.

I would also like to express my gratitude to the United States Air Force in giving me the opportunity to pursue my graduate degree. I would like to give special thanks to Dr. James P. McGuirk for taking a chance and accepting me into the graduate program at Texas A&M University. I will be forever grateful.

Thanks to all of the Air Force Institute of Technology students at Texas A&M for their support and friendship. Several other students need to be thanked as well. Eric Livingston, Al Silver, and Bill Carle all gave advice and support that helped me tremendously.

Most importantly, I want to thank my wife Amy and daughter Briana for their love, patience, and understanding while I completed my degree.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE | Page

FIGURE | Page

LIST OF TABLES

CHAPTER I
INTRODUCTION

Whiteman Air Force Base (AFB), Missouri, is the home of the Air Force's newest and most advanced aircraft, the B-2 stealth bomber. Only 20 aircraft are scheduled to be built, at an average cost of over 750 million dollars each. In view of the small number and high cost of these aircraft, protection of these assets and safety of the aircrews is a top Air Force priority. Because weather is frequently a factor in aircraft mishaps, precise weather forecasting, especially of thunderstorms and associated phenomena, is critical in protecting aircraft, both in the air and on the ground.

Accurate forecasting of "good" weather allows military personnel to maximize training opportunities. Similarly, accurate forecasting of thunderstorms allows personnel to make preparations to protect resources and property; delay, reschedule, or divert aircraft missions; and ensure the safety of other personnel. However, the forecasting of changing weather conditions is not strictly a yes or no decision. The timing of the event is just as important. Time sensitive operations depend on the weather station's forecast of onset, duration, and end of the thunderstorm event. For example, when thunderstorms occur within five nautical miles (9.3 km) of a base, all flight operations are suspended, including aircraft maintenance and refueling, due to the potential hazard from cloud-to-ground (CG) lightning. Therefore, thunderstorms which are not forecast or are poorly timed could possibly result in unnecessary loss of life and resources.

Military weather forecasters are rarely assigned to a base for more than three years. Therefore, the duty forecaster is frequently inexperienced on weather conditions and patterns for that region. Furthermore, due to the high turnover of personnel and training techniques unique to the military, weather personnel are frequently new to the career field and have little or no forecasting experience. Finally, the typical military forecaster has additional duties during their shifts, such as flight briefings, that take up a significant amount of time. The combination of inexperience and lack of time for a

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The citations on this and subsequent pages follow the style of the *Monthly Weather Review.*

thorough analysis of atmospheric conditions frequently leads to mediocre terminal airdrome forecasts for the base.

Forecasters at Whiteman AFB have several effective methods gathered over the years associated with thunderstorms, but have few good scientific thunderstorm studies for use and no known studies of lightning activity for their area. The first purpose of this study was to develop CG lightning summaries for a defined area around Whiteman AFB. Lightning data from 1989 through 1995 were examined to determine trends and values in the characteristics of CG lightning, to include ground flash density, positive ground flash density, percent positive, and first stroke median peak current. Diurnal distributions and favored start, stop, and peak times of lightning flashes were evaluated. Lightning activity for 1993 and 1994 was compared with surface observations at Whiteman AFB to determine ratios of thunderstorm activity in the area with thunderstorms occurring on base.

The second purpose of this study was to develop a quick and easy to use decision method that would increase the accuracy of thunderstorm forecasts made at Whiteman AFB. Thermodynamic and stability indices derived from rawinsonde soundings of upper-air data gathered at Topeka, Kansas and Monett, Missouri were examined for thunderstorm and non-thunderstorm periods. The data were divided into three seasons, spring, summer, and fall, to determine seasonal values and trends. Correlation coefficients of these different indices are computed to determine which indices are most useful for thunderstorm prediction. An analysis was performed to examine the differences in the parameter values between thunderstorm and non-thunderstorm periods. A logistic regression routine was determined for both locations for each season utilizing the best indices as determined by statistical analysis. The regression equations formulated produced a thunderstorm/non-thunderstorm response. Finally, decision methods were developed for each season that combined the responses from the regression equations of each rawinsonde location. In addition, considerations such as frontal system location, critical values of stability indices, and significant other factors were also included. The final products were tested against an independent data set and compared against results from other studies.

CHAPTER II
BACKGROUND

Whiteman Air Force Base is located 3 kilometers (km) south of Knob Noster, MO, and approximately 100 km east-southeast of Kansas City, at 38.73°N, 93.55°W. The base area totals approximately 11 400 hectares at an average field elevation of 263 m above sea level. The area analyzed in this study is a rectangular box around Whiteman AFB. Figure 1 is a map of the region with this box superimposed. This box extends from 50 nautical miles (nm) (92.6 km) north and south of 38.73°N, 93.55°W, 50 nm west of this point, and 25 nm (46.3 km) east of this point. This skewness is due to storms generally moving from the southwest through northwest eastward towards the station, and are monitored when they move within 50 nm of the base. Various advisories concerning flight operations are issued when thunderstorms move within 25, 10, and 5 nm of the base. Thus, thunderstorms more than 25 nm northeast through southeast of the station do not normally pose a threat to operations. A box was used instead of a circular area to increase the areal coverage to include the Kansas City area. Therefore the region around Kansas City could be analyzed to study the possible urban heat island effects on CG lightning flash densities.

Many studies have been conducted, especially in the last 25 years, to observe characteristics of CG lightning. These studies have greatly intensified over the last 15 years with the advent of the lightning detection system (Krider et al., 1980; Orville et al. 1983). The main purpose of the studies on lightning characteristics has been to develop local climatologies and numerical averages of these characteristics in order to improve automated forecasts of thunderstorms and associated lightning. While previous studies of lightning summaries on a national scale have included the Whiteman area, no known studies have been conducted specifically for this region on a more localized scale.

Prior research has been conducted relating thermodynamic and stability indices to thunderstorms (Stone, 1985; Jacovides and Yonetani, 1990). These studies correlated indices to surface and/or radar observations of thunderstorm activity. However, thunderstorms not in the immediate area of an observing station may not be reported.

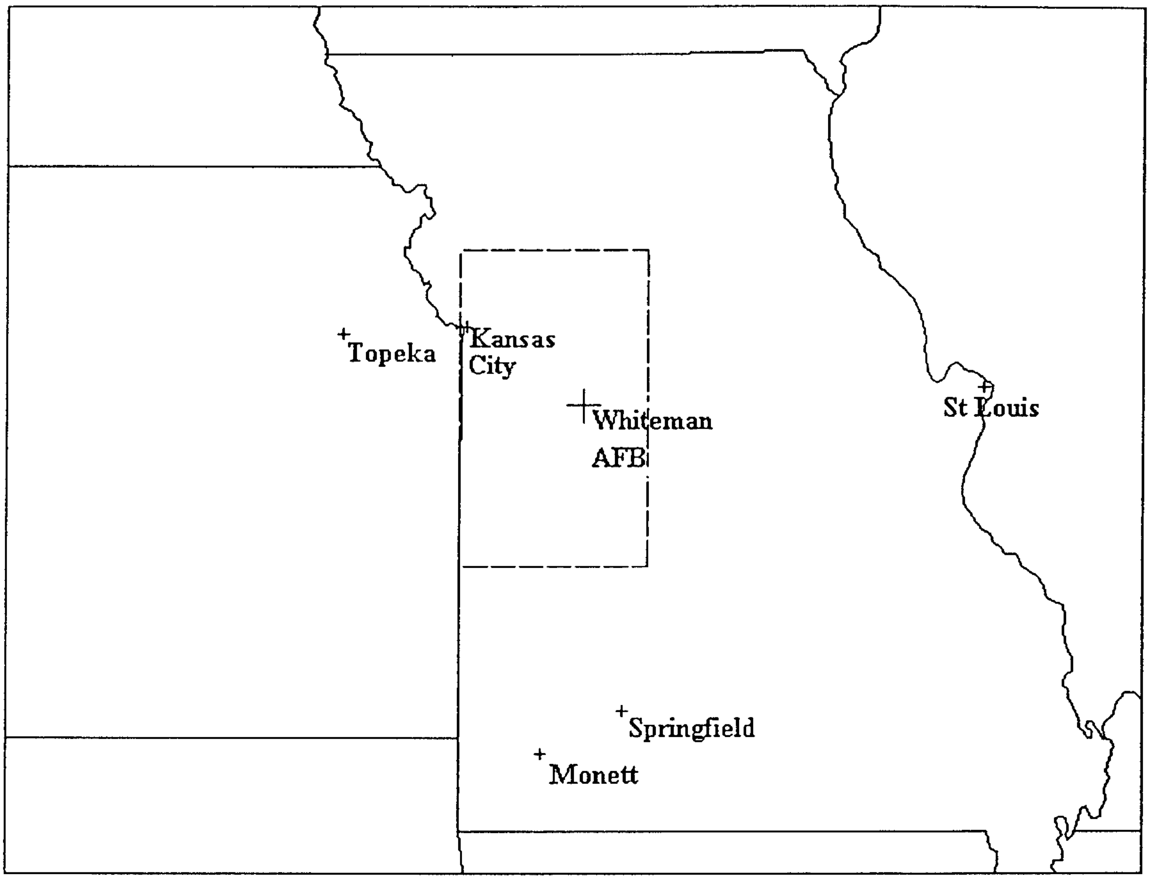

Figure 1. Map of Missouri and surrounding area. Dashed box denotes region of study. Topeka, Monett, and Springfield are rawinsonde locations used in this study.

Similarly, radar observations are based on empirical echo intensity levels that may miss weaker thunderstorms or misinterpret heavy rain showers as thunderstorms. A more reliable indicator of thunderstorm activity over an area is to use lightning data. Nevertheless, very few studies have correlated lightning activity to stability indices and thermodynamic variables. As previously mentioned, few if any thunderstorm studies have been conducted specifically for the Whiteman AFB area. The first section reviews past studies related to lightning summaries. The second section reviews studies on the relationship between thunderstorm activity and both stability indices and thermodynamic variables.

1. Lightning studies

a. Ground flash density

Orville (1991, 1994) published the first known annual ground flash densities for the contiguous United States for 1989 and 1989-1991, respectively. He reports maximum values for each year are found over central Florida, with values of 10 flashes km^{-2} for 1989, 11 flashes km^{-2} for 1990, and 13 flashes km^{-2} for 1991. West-central Missouri has reported values of 3-5 flashes km^{-2} for 1989 and 1991 and 5-7 flashes km^{-2} for 1990.

Not surprisingly, summer (June-August) is the most active period of the year for lightning flashes in the continental United States. Silver (1995) analyzed monthly ground flash densities for the United States for 1989 through 1994. He observes that while monthly maxima for July are usually located in central Florida, northwestern Missouri has the maxima for July of 1993. This maximum, though unusual, is not totally unexpected due to the unprecedented rainfall amounts and flooding which occurred in the Midwest during the summer of 1993. Silver also finds high interannual variability in the Midwest from April through November with monthly values frequently varying by as much as a factor of 12 even in July.

Because these studies are for the entire United States, the minimum grid resolution of these studies (73 km by 68 km) may be too large to resolve smaller scale variations in ground flash densities. For the summer months of Silver's (1995) study, Missouri is in a broad flash density contour of 2.9-10 flashes km^{-2}. Furthermore, due to the small sample size of six years of data, a disproportionate amount of flashes (such as July, 1993) would

affect the average for that particular time period.

On the sub-synoptic scale, can a preferred track of storms be located using ground flash densities? If so, are there features that may influence storm systems to prefer specific locations? Lopez and Holle (1986) analyzed lightning activity in northeast Colorado during the summer of 1983. After comparing surface wind maps for areas of convergence, radar echoes, and lightning data; they claim that spatial distributions of lightning are the result of topographic features and contrasts in the terrain. They are quick to point out that lightning distributions may be less patterned over more uniform terrain due to a lack of local forcing.

Reap and MacGorman (1989) performed a two year study for most of Oklahoma. After examining ground flash densities for nearly two million flashes, they find no significant relationship between terrain elevation and lightning strikes. However, the terrain variations within their study area were small compared to those studied by Lopez and Holle. Terrain variations in west-central Missouri are similar to those found in eastern Oklahoma.

Some scientists have proposed that the presence of large urban areas may affect the distribution of lightning densities. Westcott (1995) examined four years of summertime CG lightning flash densities in and around 16 central United States cities. Her results indicate that these densities are greater within and downwind of most of the urban areas. In fact, the Kansas City area shows an almost 50% increase in lightning frequency in the urban area as compared to upwind of the city. No single factor is found to explain the observed increase around urban areas, but several theories are postulated. Among these are that the cities act as a source of: (1) heat, which may further destabilize air flowing over the city; (2) cloud condensation nuclei from industrial processes; and (3) frictional lift which promotes convection.

Finally, individual storms, especially mesoscale convective complexes (MCC), produce large numbers of lightning flashes. Goodman and MacGorman (1986) report that during the most intense phase of its life cycle, a single MCC can produce one-fourth of the mean annual CG lightning at a site as it moves over the area. Thus a particularly intense storm over one portion of a region or several storm systems passing near the same

location will affect the flash density of that region for the entire year.

b. Diurnal cycle

Studying the diurnal cycle of lightning is important for determining preferred times of thunderstorm activity in a given geographic region. Several studies have discussed the diurnal variability of lightning at various locations. Lopez and Holle (1986) analyzed the diurnal variability of lightning in northeast Colorado during the Summer of 1983. They report a maximum number of flashes between 2300-2400 UTC (1600-1700 MST) and a broad minimum between 1000-1700 UTC. The first flashes occur most often between 1800-1900 UTC (32%), with over 70% of the first flashes occurring in the late morning and early afternoon between 1700-2000 UTC. The majority of days have their last flash around midnight, MST, but activity often occurs after midnight and thus times are more spread out. Reap and MacGorman (1989), in their Oklahoma study, find a broad peak in negative flashes between 2200-0400 UTC (1600-2200 CST) with a maximum peak at 0000 UTC and minimum activity around 1700 UTC. Positive flashes, which will be discussed in the next section, have a peak occurrence about 0300 UTC and a minimum also around 1700 UTC.

Lightning flashes lower both negative and positive charges to ground. While the overwhelming majority of flashes are negative, positive flashes can be significant in both overall densities and individual storms. The next sections detail studies on positive lightning and differences between characteristics of positive and negative lightning.

c. Positive flashes to ground

Orville (1994) finds a maximum in positive ground flash density for the United States for 1989 in the Oklahoma-Kansas area of 0.28-0.35 flashes km^{-2}. The overall percentages are 3.06% in 1989, 3.83% in 1990, and 3.98% in 1991. The data show a latitudinal dependence with higher percent positive lightning located to the north. The broad area around Whiteman AFB has a percentage of between 3.1% and 6.3% for each year. These values are very close to the Reap and MacGorman (1989) estimate that 4.33% of all warm season CG flashes for the central United States are of positive polarity. Monthly percentages of positive lightning flashes for 1989 through 1994 are observed for the United States (Silver, 1995). Figure 2, from Silver's study, is the monthly percentage

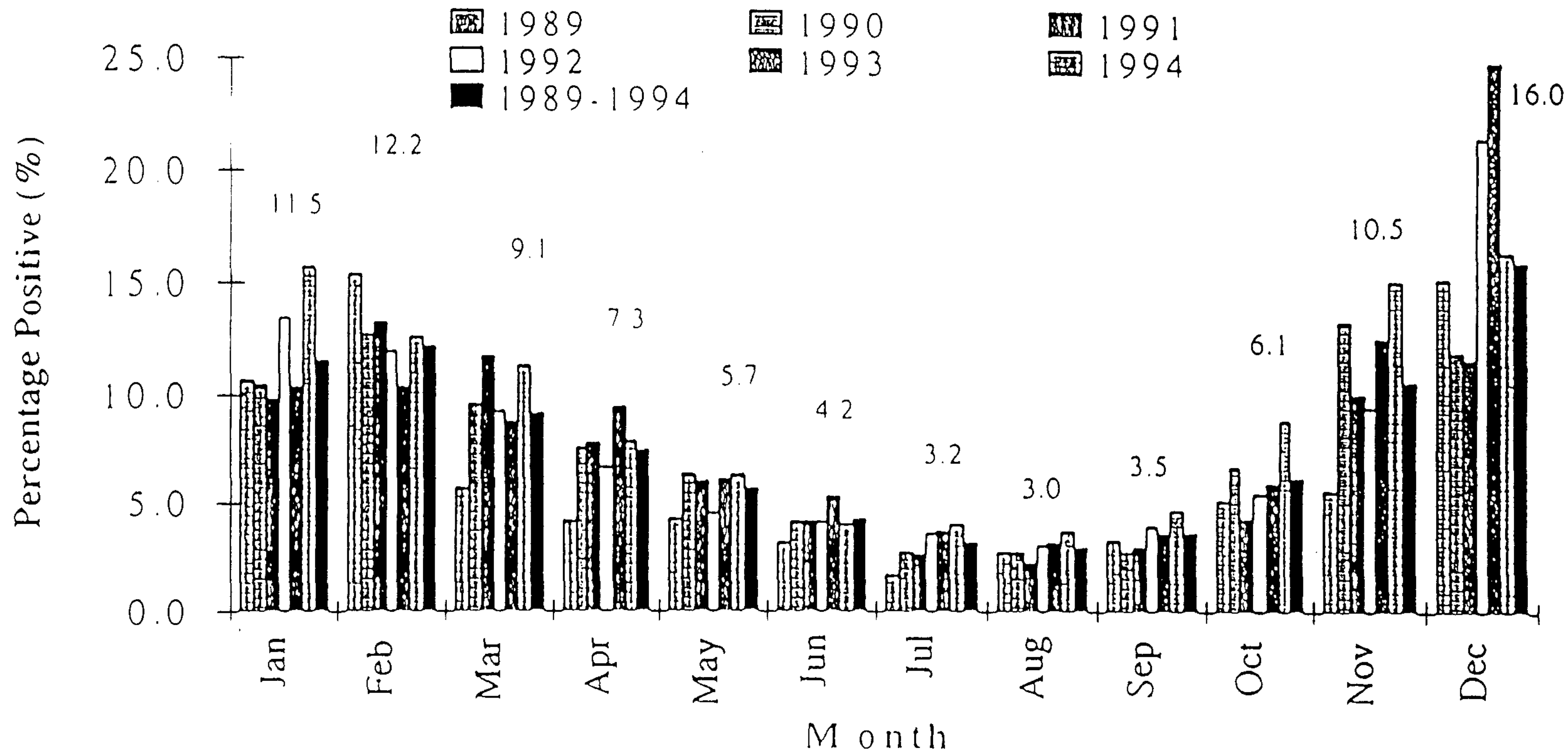

Figure 2. Monthly percentage positive lightning for each year from 1989 through 1994. The percentage positive lightning for 1989-1994 is plotted in the last column. The numbers in the graph represent the 1989-1994 percentage positive lightning. Adapted from Silver, 1995

of positive lightning for each year 1989 through 1994. Minimum value is found in the summer with an average monthly minimum observed in August of 3.0% . Maximum value is found in winter with an average monthly minimum observed in December of 16%. Regions of higher percentage positive lightning are observed in the central United States from Minnesota to Kansas during the spring and early summer, with Missouri on the fringe of this area.

Within storms, quantities of positive flashes vary in both density and percentage. High numbers of positive lightning are occasionally observed in the convective regions of thunderstorms and have been associated with severe weather. Seimon (1993), in his study of the Plainfield, IL F5 tornado of 28 August 1990, finds the predominance (91%) of positive CG flashes during development of the thunderstorm and a reversal in polarity from positive to negative over the entire thunderstorm at the time of tornado touchdown. Similar findings on other storms are noted by several other authors including Reap and MacGorman (1989), and Curran and Rust (1992).

Frequently, positive lightning is observed in the stratiform regions of mesoscale convective systems (MCS). Stolzenburg (1994) reports percentage positive lightning of 50-90% in the stratiform precipitation area, behind the main convective region. This study is conducted in the northern Great Plains where Orville (1994) finds much higher percentages of positive lightning. A study of four MCSs in the Oklahoma-Kansas region reports an average of 24% of positive lightning in the stratiform region (Holle et al., 1994). Rutledge and MacGorman (1988) study CG lightning activity in a MCC during the Oklahoma-Kansas PRE-STORM project and find a time lag of 2 hours between the maximum negative and positive lightning activity. Because the stratiform region typically contains more positive flashes, and move over an area after the main convective region, this would explain the lag in peak times between negative and positive lightning activity found by Reap and MacGorman (1989).

Orville et al. (1988) observe a pattern in which the positive flashes in a storm systematically strike ground downwind of the negative strike points. They find that the pattern has a characteristic size of about 100 km and is common year round but most frequent in winter storms. The pattern seems to be aligned with the geostrophic wind,

with the positive flash region typically located to the north and east of the negative flash region. They call this phenomenon a bipole pattern, based on the tilted bipole theory proposed by Brook et al. (1982) as the mechanism for positive CG lightning production in winter storms in Japan. According to Hill (1988), the positive charge residing on small ice crystals at upper-levels is advected downwind. This area may "outrun" the negatively charged particles in the lower regions of the cloud and become exposed to the surface of the earth. Thus a positive CG flash could be produced. Engholm et al. (1990) and Stolzenburg (1990) find similar results as Orville et al., but all find that the bipolar pattern is common in the summer as well.

d. First stroke peak current

Another characteristic of CG lightning flashes is peak current. Both positive and negative flashes exhibit differences and seasonal trends in this characteristic.

Peak current for both negative and positive flashes has been measured by several investigators over the past 20 years. Since currents were previously measured only for the first stroke of a flash by the lightning detection networks, most research has focused only on first stroke peak current.

Orville et al. (1987) observe that the peak signal strength of positive flashes is 50% higher than that of negative flashes. They also find that monthly values for both positive and negative peak currents in the United States are highest in winter, lowest in summer. Silver and Orville (1995), in their study of lightning in the United States for 1992 and 1993, find that lowest positive median peak currents are observed in September 1992 (32 kA) and in July and August 1993 (33 kA). Lowest negative median peak currents are 29 kA in May, June, and August 1992, and 28 kA in May and June 1993. Highest positive values are 69 kA in January 1992 and 68 kA in December and January 1993. Highest negative values are in January 1992 and 1993 of 44 kA and 46 kA, respectively. Silver (1995) shows average median peak currents for negative flashes range from 43 kA in January to 29 kA in July; while positive flashes range from 66 kA in January to 39 kA from July to September. However, Silver does not include 1994 data in his analysis. During the latter half of the year, the median peak currents he finds are much lower than other years. The introduction of time-of-arrival (TOA) detection equipment into the

NLDN in August of 1994 seems to be the most likely cause of this result.

2. Thunderstorm activity and forecasting

a. Diurnal variations

Inferences from studies of thunderstorm frequency and diurnal variations should match findings from studies of lightning variations. Easterling and Robinson (1985) conducted a study of thunderstorm starting times for a 25 year period using 450 observing stations in the contiguous United States. After analyzing seasonal and spatial variations of diurnal activity, the country is divided into nine distinct thunderstorm regions. They find that in the central states, the majority of storms occur at night, but can happen at any time. For west-central Missouri, they find a maximum starting time between 0400-0600 UTC for the summer and fall, and 0300-0400 UTC for the spring. Interestingly, their maximum period for thunderstorms in Oklahoma is about 2-4 hours later than the peak in lightning activity found by Reap and MacGorman (1989) in their Oklahoma study. Again, these differences in times could be due at least in part to observers at observing stations not being able to record thunderstorms in the area due to thunderstorms being too far away from the stations or not detected due to background noise and lighting from the surrounding area. Wallace (1975) studied data from over 100 stations in the United States. Among his findings are that while summertime thunderstorms exhibit their maximum frequency around midnight local time over the central United States, severe convective storms occur most often during the early evening. This is not surprising since diurnally the atmosphere is typically most unstable near sunset because of heating throughout the day. An unstable atmosphere in turn is conducive to convection. Thus, good indicators of convective activity are the stability indices derived from rawinsonde observations.

b. Thermodynamic and stability indices

Thunderstorm forecasting techniques combine traditional pattern recognition with concepts based on physical processes occurring within the troposphere (McNulty, 1995). Among the processes are a number of different stability indicators that forecasters evaluate to predict thunderstorm activity, including Showalter stability index (SSI), lifted index (LI), K index (KI), convective available potential energy (CAPE), convective inhibition,

surface humidity (equivalent potential temperature), water vapor advection, and a mechanism of lift. Some of the base values forecasters have found from experience are LI less than -6° C and CAPE greater than 3000 $m^2 s^{-2}$ (McNulty, 1995). Air Force Global Weather Central severe weather forecasters heavily use total totals (TT) and the Severe Weather Threat (SWEAT) index to forecast severe weather. Base values are TT greater than 50 and SWEAT greater than 300 (Miller, 1972). Unfortunately, Miller's study does not include false alarm rates for these indices. Also, the critical values are for synoptic scale regions. Some values work well at one location but not as well at another. In fact, these values may be quite different from one location to another and even from one season to another at the same location.

Another method used to relate thunderstorm activity at a given location to thermodynamic variables and stability indices from individual rawinsondes is the use of correlation coefficients. Stone (1985) correlates stability indices from nine eastern United States rawinsonde sounding locations with radar echo intensity reports from April through September of 1984. Because he considers the 0000 UTC soundings to be contaminated by convection, only the 1200 UTC soundings are analyzed. Correlation coefficients are: LI (-0.64), SSI (-0.61), and KI (0.54).

Jacovides and Yonetani (1990) evaluate several stability indices for predicting thunderstorms on the island of Cyprus. Upper-air data were analyzed from March through May for two different periods: 1970-1974 and 1984-1988. Yes/no thunderstorm thresholds were established, with a threshold value for KI of 20 and for SSI of +3. They used Yule's index (YI) (Jacovides and Yonetani, 1990) to determine skill scores, as well as the critical success index (CSI) and false alarm rate (FAR). Equations for these indices are listed in the Appendix. For KI, Jacovides and Yonetani find that YI = 0.49, CSI = 39%, FAR = 53% and YI = 0.59, CSI = 52%, FAR = 43% for the 1970-1974 and 1984-1988 periods, respectively. For SSI, they find YI = 0.52, CSI = 47%, and FAR = 48% for the 1984-1988 period. The Showalter stability index is not computed for the 1970-1974 data set.

Livingston (1995) calculates correlation coefficients for July and August of 1986 to 1993 for Georgia to produce a thunderstorm prediction model for the 1996 summer

Olympic games. He designates an active lightning day as one in which thunderstorms with greater than or equal to 1000 flashes occur within 50 km of at least three of the nine Olympic sites. An inactive day is defined as a day in which no flashes are recorded within 50 km of at least seven of the nine sites. He finds correlations of KI of 0.56, of SSI of -0.60, and a modified CAPE called CAPE 2000 of 0.70. CAPE 2000 uses the value of the level of free convection (LFC) determined by the average temperature and average dewpoint from the lowest 2000 meters as opposed to surface values for these variables.

While some indices are better than others in predicting thunderstorms at a given location, a single variable is usually not sufficient to predict thunderstorm activity. A combination of several indices would be a better indicator. A handful of studies have attempted to combine indices into a single regression equation to predict thunderstorms. Charba (1979) developed a 2 to 6 hour severe local storm forecasting system for the United States east of the Rocky Mountains using linear regression equations. He developed equations for both the Gulf Coast and non-Gulf areas due to differences in the severe weather environment for the two regions. The smallest equation uses 10 variables selected from three different sources. Charba states that while tests show that the thunderstorm forecasts are respectable in general, their individual performances are related to the strength and organization of the parent synoptic system.

Livingston (1995) produces several different logistic regression equations. Persistence, SSI, and CAPE 2000 are used in the regression equation for active lightning days versus all other days. The performance of his model on data from July and August of 1994 shows a CSI of 33% and a FAR of 50%. In the logistic regression equation for inactive lightning days versus all other days, LI, KI, relative humidity, and persistence are selected. In this case, CSI = 43% and FAR = 54% when tested on the same data.

Finally, several attempts have been made to develop rule-based expert systems to aid forecasters in the prediction of thunderstorms. Colquhoun (1987) describes a decision tree approach used not only for forecasting whether thunderstorms will occur, but also what type of phenomena (tornadoes, hail, etc.) might be expected to accompany them. A well-designed decision tree forecasting system can eliminate redundancies of less structured methods, therefore saving the forecaster valuable time. Colquhoun's decision

tree uses stability indices such as LI and thermodynamic variables such as windshear and mid-level moisture, but also includes subjective statements like "will preventative factors dominate?" as decision criteria.

Lee and Passner (1993) developed a system based on the initial logic of Colquhoun's decision tree. They use combinations of critical values for LI, SSI, TT, cross totals (XT), and vertical totals (VT), as well as information provided by the forecaster about local lifting mechanisms. Depending on the information provided about lift, a certain number of critical values must be met for thunderstorm occurrence to be predicted. Tests for several sounding locations in the United States are conducted from March through September of 1990. A "hit" is based on thunderstorms occurring within a 100 km radius of a sounding location. Results for Topeka show a CSI of 50% and a FAR of 41%.

This overview of previous studies has shown that little research has been performed on stability criteria on a sub-synoptic scale region and no studies have been done exclusively for west-central Missouri. Several of the techniques and ideas described in this chapter are incorporated into this study of thunderstorm prediction at Whiteman AFB. The next chapter is an overview of the data used and methods of analysis utilized during this research.

CHAPTER III

DATA AND METHODS OF ANALYSIS

Cloud-to-ground lightning data for this study were collected by the National Lightning Detection Network (NLDN), operated by GeoMet Data Services, Inc. Rawinsonde data for 1993 to 1995 were obtained from the Climatic Research Division, Scripps Institution of Oceanography, University of California at San Diego. Surface observations for Whiteman AFB for March through November of 1993 and 1994 were compiled and received from the United States Air Force Combat Climatology Center, Operating Location A, Asheville, North Carolina.

1. Lightning data

A CG lightning detection system now known as the National Lightning Detection Network was installed at various locations throughout the United States during the 1980's and has covered the contiguous United States since 1989. The system uses a network of over 100 ground based sensors called direction finders (DFs) that detect the electromagnetic signals produced by lightning discharges. The DFs have a nominal range of 400 km and a detection efficiency of approximately 70% (Mach et al., 1986; Orville et al., 1988). Location errors of lightning flashes detected by the network until 1994 are 5-10 km (Mach et al., 1986; Orville, 1994). As previously mentioned, a different kind of detection equipment called time-of-arrival (TOA) was integrated into the NLDN in 1994. This integration is thought to reduce the location errors to 1 km or less (Cummins et al., 1995). The lightning data from each instrument is transmitted to the Network Control Center where it is processed to provide time, location, and peak current of each detected charge. At least two DFs or TOAs must record the charge before it is accepted and the plot of the discharge is disseminated to real-time users. A more detailed description of the lightning detection system can be found in papers by Krider et al. (1980) and Orville et al. (1983), among others. Cummins et al. (1995) provide an update on the improvements made to the NLDN in 1994.

All CG lightning flashes analyzed in this study were detected by the NLDN within the box around Whiteman AFB for the period 1989-1995 (refer to Figure 1). Total flashes were broken down by month, season, and year. Seasonally, spring was defined as March-May, summer as June-August, and fall as September-November. The winter season (December-February) was not included due to the small sample size. However, flashes that were recorded during the winter months were included in all yearly and total counts. Histograms of monthly tables of CG flashes for each season were created to compare the number of flashes from one month to the number of flashes of the same month for different years.

The number of thunderstorm days in the study area per month were determined. Days are defined as from 0600 UTC to 0600 UTC of the following day (midnight-to-midnight Central Standard Time). A study of the data showed that the start and end times for a thunderstorm day did not affect the number of thunderstorm days per year. The total number of thunderstorm events per year were compared to the total number of days, and divided into categories of lightning flash amounts. A thunderstorm event is defined as at least two separate flashes being recorded in the region of study within two hours. Separate events are characterized by at least two hours between the time of last flash for one set and first flash of the next. Categories of flashes are on a logarithmic scale of 2-10 flashes (category 1), 11-100 flashes (category 2), 101-1000 flashes (category 3), and greater than 1000 flashes (category 4). This raw count of CG flashes was not scaled. Finally, ratios of thunderstorm events in the defined area to thunderstorm events occurring on the base were established.

The number of positive CG lightning flashes detected in the study region were totaled for each month, season, and year. By comparing these numbers with the number of total flashes recorded over the same time periods, percentages of positive lightning were determined. These percentages were compared to each other in order to locate any increases or decreases which may have taken place. For large variations in percentages, individual storms were analyzed to find any unique events which may have influenced the statistical results.

All lightning flashes detected were stored into one hour bins. All flashes which occurred from H+00:00 to H+59:59 were referenced to the preceding cardinal hour. The total number of flashes for all 7 years were computed versus time of day for the entire period to determine the diurnal variation of CG lightning in the study area. Flashes were then divided into seasons and recomputed versus time of day to find any seasonal differences in their diurnal variations. Diurnal characteristics were also resolved for positive lightning flashes on a seasonal basis as well. Both the number of positive flashes and the percentage of positive flashes were examined versus the time of day.

The times of first and last flash of each thunderstorm event were catalogued and analyzed to ascertain preferred beginning and ending times of lightning activity in the region on a seasonal basis. To check if there were preferred times for more organized convection, category 1 and 2 events were deleted and the remaining data reexamined for each season. The length of time from first to last flash of all category 3 and 4 events in each season were averaged to determine the mean duration of these events.

The ground flash density (GFD) was determined in an attempt to establish preferred locations of lightning flash activity. The GFD is the number of lightning strokes to ground per square kilometer. Grid resolution for the study area was 5.4 by 4.2 km. Gridded data were scaled by a factor of 1.4 to account for the assumed 70% detection efficiency of the network. The data were then mapped for selected time periods and contoured to produce maps of the GFD. For average ground flash densities, the scaled total number values of each time period (seasons or years) were divided by the number of years in the data set. Seasonal maps of average GFDs were thus created. An average yearly GFD map was developed as well. Ground flash densities were compared with topographical maps of the area to determine if terrain features had an effect on spatial distribution. Ground flash density maps for selected years were constructed to demonstrate the year-to-year variability. Tests were performed to determine if GFD averages or patterns were affected by factors such as individual storm systems with high amounts of CG lightning or yearly distributions of lightning flashes.

Ground flash density maps were made for positive lightning flashes. Because the

number of positive flashes was much smaller than the overall number of flashes, contour values were much less than those for total flashes as well. Positive GFD maps were constructed on an average seasonal and yearly basis. These maps were compared with GFD maps for total flashes in order to locate any evidence of bimodal CG lightning patterns in the study area.

First stroke mean peak current was measured for both positive and negative polarity flashes. Monthly and seasonal variations of mean peak currents were compared and contrasted. It is claimed by Cummins et al. (1995) that more flashes of lower current are being recorded by the NLDN since the range was increased and the TOA system was integrated into the network in 1994. The number of both negative and positive flashes recorded in the study area were determined for designated increments of peak current values to find out how many flashes of lower peak currents were recorded on a yearly basis. Finally, the cumulative percentage of negative and positive flashes above peak current values for the period 1989 through 1993 were compared against the same data for 1994 and 1995. This was another way to show how much more lightning of lower peak current was measured by the NLDN after the upgrade.

2. Sounding data

Rawinsondes are instruments used to take vertical measurements of the atmosphere over a particular point. Rawinsondes include sensors for measuring temperature, humidity, pressure, wind speed, and wind direction from the surface to heights greater than 15 km. Soundings are typically conducted twice daily, at 0000 UTC and 1200 UTC. While airborne, measurements are taken continuously and reported at prescribed levels or when abrupt changes occur in temperature or humidity.

The data collected from all rawinsondes give estimates of atmospheric conditions over a region, such as a country or continent. These composites give a good indication of large scale features and discontinuities that control weather patterns. However, because rawinsonde locations are usually spaced several hundred kilometers apart, these point measurements frequently miss features on the mesoscale level that are also important.

On a more localized level, sounding data can provide a good indication of atmospheric conditions. Furthermore, by deriving stability indices from measurements made by a rawinsonde, it is possible to establish a set of atmospheric conditions favorable for certain weather regimes.

Forecasters at Whiteman AFB plot and analyze upper-air soundings from Topeka, Kansas and Springfield, Missouri. Topeka is located approximately 190 km west of Whiteman AFB, while Springfield is located approximately 175 km to the south of the base. Prior to May, 1995, the rawinsonde location currently at Springfield was located at Monett, Missouri, about 205 km south of Whiteman. Figure 1 shows the locations of all three of these sites. Soundings were obtained from both Monett and Topeka for the period March through November of 1993 and 1994. Sounding data were divided by location into seasonal categories to determine seasonal values and trends. The sounding data for each location were then divided further into thunderstorm and non-thunderstorm periods. If at least two CG lightning flashes were recorded in the box around Whiteman AFB within 13 hours after a sounding was taken, that period was considered a thunderstorm period. If no flashes occurred, the period was classified as a non-thunderstorm period. Thirteen hours instead of 12 hours was used to include a 1 hour time lag that normally occurs between the time the sounding is taken and the time it is disseminated to the base.

Of the 368 possible sounding periods, 82 thunderstorm periods were identified for the spring seasons of 1993 and 1994. Of these, 80 soundings were used from Monett and 64 were used from Topeka. Therefore 286 sounding periods are classified as non-thunderstorm periods. To analyze every sounding for this season, not to mention summer and fall, is beyond the scope of this study. However, a potential problem exists in using all available thunderstorm soundings and only a sample of non-thunderstorm soundings. This problem is overcome by using a stratified random sampling technique of non-thunderstorm soundings based on the average number of thunderstorm days per month. The average number of thunderstorm days over the study area varies by month, with more thunderstorms normally occurring in May than in March. Thus, if the ratio of non-

thunderstorm soundings selected by month is the same ratio that thunderstorm days occur, the resulting data set should be a very close reflection of the total soundings available. Therefore, 80 non-thunderstorm periods were selected for comparison from the spring seasons. All 80 soundings were available from Monett, 79 from Topeka.

For both thunderstorm and non-thunderstorm periods, soundings were not used if they included erroneous or missing essential information used to determine the selected stability indices and thermodynamic variables. Furthermore, soundings were not used for thunderstorm periods if they were taken from an airmass different than one in which thunderstorms occurred, such as after frontal passage through Topeka but not yet past the study area.

For the summer seasons, 166 soundings were used from Monett and 155 were used from Topeka. Seventy-nine soundings were available from Monett and 74 from Topeka for non-thunderstorm periods. Finally, for the fall seasons, 61 soundings were used from Monett, only 50 from Topeka. All soundings from 64 non-thunderstorm periods selected were available for both locations.

Ten stability indices and two thermodynamic variables derived from the soundings were selected for analysis. These 12 stability indices were: (1) Showalter stability index; (2) K index; (3) lifted index; (4) total totals; (5) cross totals; (6) vertical totals; (7) severe weather threat index; (8) surface equivalent potential temperature; (9) 925 mb equivalent potential temperature; (10) CAPE; (11) CAPE 1000; and (12) CAPE 2000. See the Appendix for definitions and formulas for each of these indices.

Correlation coefficients were determined which evaluated the correlation of the 12 indices when thunderstorm and non-thunderstorm periods were compared. These coefficients were determined for indices from both locations on a seasonal basis. To derive correlations, values of the indices and variables were individually compared for thunderstorm and non-thunderstorm periods. A thunderstorm period was assigned a dummy value of +1, while a non-thunderstorm period was assigned a value of -1. The numbers assigned to the two periods were arbitrary and had no effect on the correlation.

Only about 9% of category 1 and 2 events catalogued over the two year period occurred at Whiteman AFB. Therefore, only category 3 and 4 events were compared with non-thunderstorm periods to redetermine coefficients in an attempt to find better correlations.

Means and medians of the 12 variables for category 3 and 4 events were compared with those of non-thunderstorm periods. In addition, the lower quartile values of the indices for thunderstorm events were computed to show critical values for those indices.

For each season and location, the values of all ten stability indices and the two thermodynamic variables for all non-thunderstorm periods and all category 3 and 4 thunderstorm events were entered into a statistical analysis program. Then a logistic regression program was invoked. As with the correlations, a thunderstorm period was assigned a value of +1 and a non-thunderstorm period assigned a value of -1. The result was a linear equation used to predict a binary response of a thunderstorm or non-thunderstorm period. A thunderstorm event was predicted if the regression response value was a positive number. On the other hand, a negative response value was a prediction of a non-thunderstorm period. The six resulting equations were first tested on their respective dependent data sets, and then on an independent data set of 1995 sounding data from their respective seasons and locations.

Both a stepwise selection process and a backward elimination process were invoked to produce initial regression equations. Stepwise selection begins by producing the optimum one-variable model. Other variables are entered in a step by step process until none of the remaining variables meet a preselected significance level for entry into the model. Backward elimination begins by taking all the variables and producing an equation, then systematically eliminating variables that contribute least to the model. The equation is recomputed, and the process is repeated, until only variables that again meet the predetermined significance level remain.

In three of the six cases, both processes produced the same usable equation. In one of the remaining three cases, the two different equations were tested against both the

dependent and independent data set. The equation which performed best in these tests was selected.

In the other two cases, each process produced different equations as well. However, these equations performed so poorly on tests that they were not used. In several of these equations, parameter estimates of one or more of the variables selected for inclusion were of opposite sign to the parameter correlations. Therefore, the regression equations for these two cases were constructed by forcing the processes to accept some variables and automatically reject some others. The resulting equations were then tested and the best of these equations were selected for use.

For each equation that was tested, skill scores were determined to evaluate their effectiveness of thunderstorm/non-thunderstorm prediction. These skill scores consist of the critical success index, the false alarm rate, the probability of detection, and Yule's index. A summary and equations of these indexes are in the Appendix. More detailed descriptions of these indices, and their usefulness and relevance, are described by Jacovides and Yonetani (1990).

The responses of the two equations for each season were compared to examine their differences and similarities. A matrix was developed comparing the results from each pair of equations for each individual sample taken from their respective 1995 test season. This matrix shows the number of samples in which both equations had positive responses, the number of samples in which both equations had negative responses, and the numbers of samples in which one equation was positive and the other negative.

Analysis was performed on the samples in which the equations differed to determine a way to decide which equation was correct. Results from this analysis were used to develop decision method models for predicting thunderstorms at Whiteman AFB during the spring, summer, and fall seasons.

CHAPTER IV
RESULTS

1. Lightning summary

a. Temporal distribution and variability

Assuming that the detection efficiency of the NLDN has remained around 70% throughout the period of study, comparisons on the total number of CG lightning flashes recorded by the network can be made. The total number of lightning flashes for the years 1989 through 1995 are listed in Table 1. Table 2 shows the total number of flashes, yearly average, standard deviation, and coefficient of variation of flashes by month and season for the area. Numbers of flashes were broken down by month and season for each year. A large variability in the number of flashes was apparent between years. The number of flashes varied from 75 149 in 1989 to 174 447 in 1993. However, it must be remembered that 1993 was the year of the tremendous summer flooding in the Midwest. This was clearly reflected in the flash count, as the number of flashes for 1993 was more than 60% higher than the second highest number of flashes, recorded in 1990. Not counting 1993, the number of CG flashes for each year were between 30 000 flashes of one another, a 42% difference. With the overall average number of CG flashes per year approximately 102 250, all years except 1993 were within one standard deviation of the mean.

On average, the frequency of CG flashes increased from January to March, followed by a rapid increase in April through June, to the maximum number of flashes in July. The activity then decreased slightly in August, falling off rapidly from September until it reached a yearly minimum in December. This pattern generally held true for individual years, although some variability was evident. In fact, the month of peak activity in 3 of the 7 years was August, with July being the month of peak activity only once, in 1992. Another example was April and May of 1994. In April, 19 687 flashes were recorded, over 3 1/2 times the May number of 5221. These month-to-month variations even out over each season. As expected, the majority of flashes occurred in the summer season. Overall, approximately 63% of all CG flashes occurred in the summer months from 1989 through 1995. The most flashes were consistently recorded in the summer

Table 1. The number of cloud-to-ground lightning flashes recorded by the NLDN per month, season, and year for 1989 through 1995. Seasons are denoted by spring (March-May), summer (June-August), and fall (September-November).

	YEAR						
PERIOD	1989	1990	1991	1992	1993	1994	1995
JAN	245	144	3	1	4	55	104
FEB	0	19	75	687	37	16	1064
MAR	1145	1226	724	596	2559	1207	1804
APR	1511	934	9197	10534	10940	19687	4330
MAY	6736	21811	16711	2731	10966	5221	26763
JUN	10058	49496	13545	2546	30069	21474	19418
JUL	15549	17441	12188	31783	43885	16910	24772
AUG	32027	6523	15378	5738	48967	24518	8482
SEP	4750	1953	11550	18642	23560	3981	7262
OCT	2899	6570	8540	865	2873	3078	2452
NOV	229	640	212	2737	444	1274	472
DEC	0	14	0	2	143	57	2
SPRING	9392	23791	26632	13861	24465	26115	32897
SUMMER	57634	73460	41111	40067	122921	62902	52672
FALL	7878	9163	20302	22244	26877	8333	10186
TOTAL	75149	106771	88123	76862	174447	97478	96925

Table 2. Total number of flashes, average per year, standard deviation, and coefficient of variation per month, season, and year for 1989 through 1995. Seasons are as denoted in Table 1.

	TOTAL #	AVERAGE	STANDARD	COEFFICIENT
PERIOD	OF FLASHES	PER YEAR	DEVIATION	OF VARIATION
JAN	556	80	85	1.06
FEB	1898	271	396	1.46
MAR	9261	1323	621	0.47
APR	57133	8162	6076	0.74
MAY	90939	12991	8368	0.64
JUN	146606	20944	14207	0.68
JUL	162528	23218	10396	0.45
AUG	141633	20233	14846	0.73
SEP	71698	10243	7527	0.73
OCT	27277	3897	2470	0.63
NOV	6008	858	835	0.97
DEC	218	31	49	1.58
SPRING	157153	22450	7466	0.33
SUMMER	450767	64395	26259	0.41
FALL	104983	14998	7310	0.49
TOTAL	715755	102251	31311	0.31

season, with the spring season recording the second most flashes in 5 of the 7 years.

Comparing the same months of different years revealed a large variability in the number of flashes. Figure 3 is the monthly total of flashes during the spring season for each year. Figure 4 is the monthly total of flashes during the summer season for each year. Figure 5 is the monthly total of flashes during the fall season for each year. An examination of these figures shows that monthly flash totals varying by a magnitude of five are not uncommon. In fact, June totals varied from 2546 flashes in 1992 to 49 496 flashes in 1990, a factor of almost 20.

Seasonal values varied from year to year as well. The winter season was not included due to the low number of lightning flashes recorded during this period. The other three seasons show about the same variability year-to-year, varying by a magnitude of over three.

In addition to the low year-to-year variability in lightning flashes, with the exception of 1993, the number of thunderstorm days per year was also remarkably consistent. Table 3 lists the number of thunderstorm days for the defined region by month during each year of the period. A thunderstorm was said to occur if at least two flashes were recorded within 2 hours of each other in the area. Additionally, a thunderstorm day was defined from 0600 UTC to 0600 UTC (midnight-to-midnight CST), to coincide with times for thunderstorm days used by the National Climatic Data Center. Thunderstorm days per year ranged from 93 in 1989 to 114 in 1993, a difference of only 23%.

A comparison of Table 3 to Table 1 shows that in 1992 for example, about 77 000 flashes were recorded over 106 days, while almost 175 000 flashes were recorded in 114 days in 1993. Since no instrumentation changes or modifications were made during this period, we can assume that the increase in flashes were due to Nature. Almost 100 000 more flashes were recorded in only six more thunderstorm days. Therefore, a large day-to-day variability in lightning flashes is apparent. On the other hand, only about 500 more flashes were recorded in 1994 than 1995, but in 11 more days (108 to 97). It is known that several upgrades were made to the NLDN in 1994. These upgrades may have improved the detection efficiency so that more flashes were detected in 1995. More evidence for this improved detection efficiency can be seen in the section on peak current.

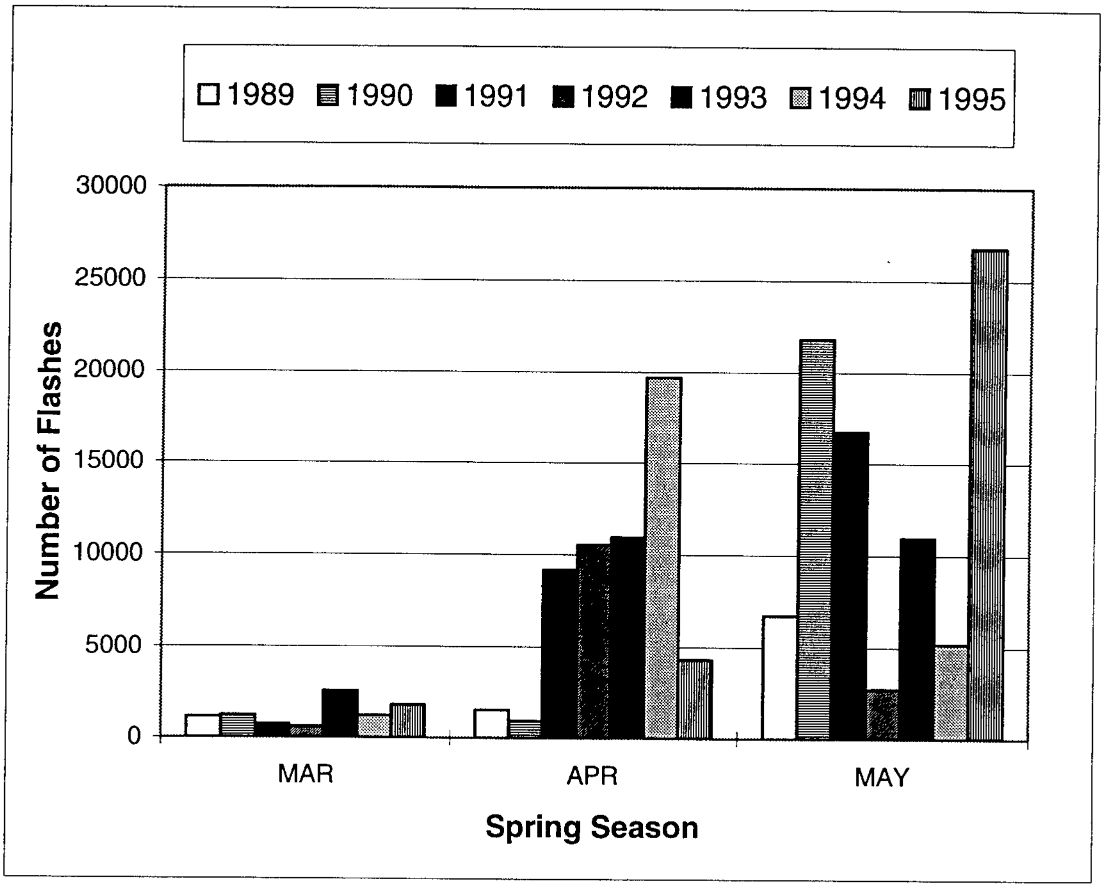

Figure 3. Monthly totals of cloud-to-ground lightning flashes during the spring season (March-May) for 1989 through 1995.

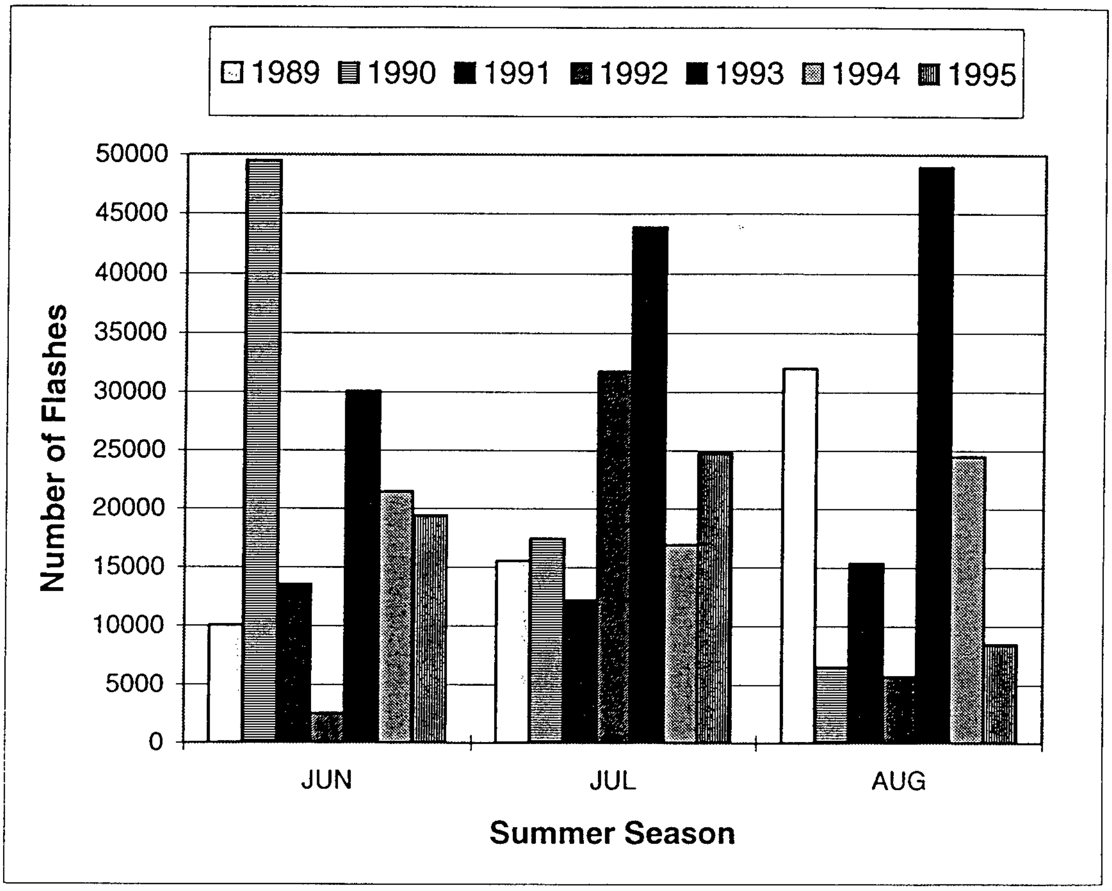

Figure 4. Monthly totals of cloud-to-ground lightning flashes during the summer season (June-August) for 1989 through 1995.

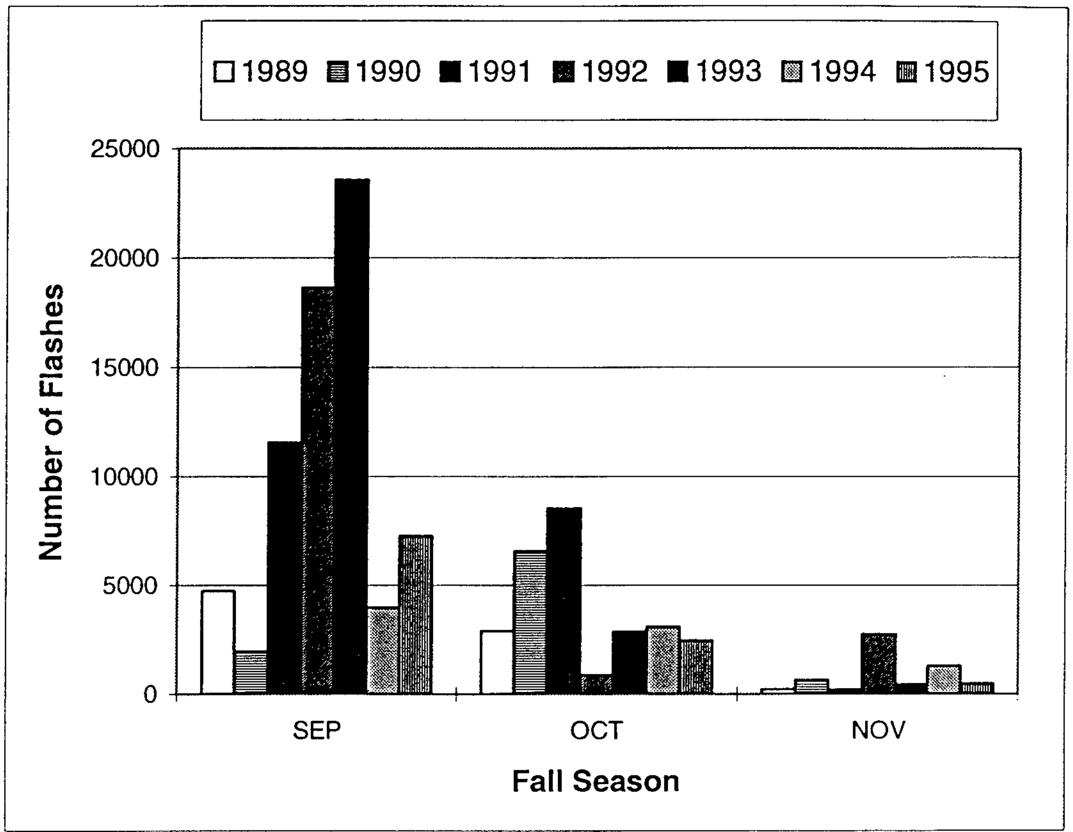

Figure 5. Monthly totals of cloud-to-ground lightning flashes during the fall season (September-November) for 1989 through 1995.

Table 3. The number of thunderstorm days per month, season, and year for 1989 through 1995. Thunderstorm days are defined from 0600-0600 UTC (midnight-midnight CST). Seasons are denoted by spring (March-May), summer (June-August), and fall (September-November).

	YEAR						
PERIOD	1989	1990	1991	1992	1993	1994	1995
JAN	2	4	1	0	1	2	3
FEB	0	3	3	2	4	1	1
MAR	6	7	6	9	3	4	6
APR	5	13	12	11	8	13	11
MAY	11	17	20	8	18	7	12
JUN	18	22	14	12	22	20	16
JUL	18	18	14	27	25	18	16
AUG	18	13	19	12	13	18	12
SEP	7	8	13	11	13	6	11
OCT	6	5	7	7	3	11	6
NOV	2	1	1	6	3	6	3
DEC	0	2	0	1	1	2	0
SPRING	22	37	38	28	29	24	29
SUMMER	54	53	47	51	60	56	44
FALL	15	14	21	24	19	23	20
TOTAL	93	113	110	106	114	108	97

Table 4. Number of thunderstorm events categorized by the number of cloud-to-ground lightning flashes produced by each event for the seven year period 1989 through 1995. Category 1 denotes 2-10 total flashes. Category 2 denotes 11-100 total flashes. Category 3 denotes 101-1000 flashes. Category 4 denotes greater than 1000 flashes.

	CATEGORY OF FLASHES				TOTAL #	TOTAL #
YEAR	1	2	3	4	OF EVENTS	OF DAYS
1989	32	26	36	19	113	93
1990	30	35	32	22	119	113
1991	32	32	43	27	134	110
1992	42	37	36	24	139	106
1993	26	40	28	37	131	114
1994	26	41	31	26	124	108
1995	27	32	34	31	124	97
TOTAL	215	243	240	186	884	741

Another way to measure the day-to-day variability is to measure the variability of lightning flashes in thunderstorm events. A thunderstorm event was defined as at least two CG lightning flashes occurring, with separate events differentiated by at least two hours between the time of last flash for one set and first flash of the next. Each event was then catalogued according to the total number of flashes recorded in the region during the event. Table 4 gives the breakdown of events by category for each year. Categories were based on a log base 10 scale and numbered one through four. Inspection of Table 4 reveals that the number of thunderstorm events was not necessarily correlated with the number of thunderstorm days for each year. For example, 1994 and 1995 had the same number of events, but a different number of days. Hence, several events may have occurred on the same day. Similarly, a single event beginning before 0600 UTC and lasting until after 0600 UTC would have encompassed two thunderstorm days. In addition, a large number of events did not mean a large number of flashes for a given year. The highest yearly total number of events was in 1992, which has the second lowest total number of flashes. Conversely, 1993 had the third highest number of events, but many more flashes than any other year.

Category 2 and 3 events occurred with about the same frequency. Furthermore, these two categories averaged about three more events per year than category 1 and seven more events per year than category 4. Thirty-eight events were recorded over the period in January, February, and December, but only five were of category 3 or 4. If these events aren't counted, categories 3 and 4 occurred at about the same frequency as categories 1 and 2, with 425 category 1 and 2 events recorded compared to 421 category 3 and 4 events for March through November of the entire period.

The number of flashes in a thunderstorm event ranged from two on 67 different occasions to 27 601 on 11 and 12 August 1993. Thirty-six events over the seven year period had over 5000 recorded flashes. Ten of those events were reported in 1993 and eight in 1990, the two years with the highest number of flashes.

Since this study was related to predicting thunderstorms at Whiteman AFB, thunderstorm events for a given month for the box around Whiteman AFB were compared to the number of thunderstorms reported at the base for the same month. Thunderstorm

events from March through November of 1993 and 1994 were compared to surface observations taken at Whiteman AFB for the same period (Table 5). On average, observers at Whiteman AFB recorded thunderstorms about 41% of the time that lightning was detected in the box. However, no category 1 events occurred at the base, and only 15% of category 2 events were reported at the base. On the other hand, 55% of category 3 and 90% of category 4 events were recorded at the base. Table 5 also lists the days with thunderstorms for each month during the period for both the study area and Whiteman AFB. Thunderstorm days were recorded at the base approximately 50% of the time that thunderstorm days occurred in the box. Although some variability was apparent on a monthly basis, the overall number of thunderstorm days at the base compared favorably to the climatic average, even with regards to the excessive precipitation and lightning flash amounts recorded in 1993.

Although the large majority of CG lightning flashes that occur in the United States are of negative polarity, positive lightning flashes are significant in number. Positive polarity CG lightning flashes were separated from the total lightning flash set and the same kinds of analysis used on the total number of flashes were performed. Once again, the data were further separated by months, seasons, and years.

Table 6 shows the number of positive flashes per month and season for the period 1989 through 1995. Typically, few positive flashes occurred during the first few months of the year, then a large increase was observed from April until the maximum number of flashes was reached in July. The number of positive flashes then decreased quickly from August through December, when the minimum number of flashes was observed.

A comparison of seasons showed that the number of positive flashes recorded over the last three years was much higher than for the first four years. That was expected for 1993, when almost twice as many CG lightning flashes were recorded than in any other year. However, that was not the case with 1994 and 1995. Almost twice as many positive flashes were recorded in those two years than in the first four years, yet their total flash counts of positive and negative lightning were similar.

By comparing these totals to the total number of flashes in Table 1, the percentage of lightning flashes of positive polarity was determined. Figure 6 shows the average

Table 5. Number of thunderstorm events in the defined region compared to the number of thunderstorm events reported at Whiteman AFB from March through November of 1993 and 1994. TSTM stands for thunderstorm. Category 1 denotes 2-10 cloud-to-ground (CG) lightning flashes per event. Category 2 denotes 11-100 CG lightning flashes. Category 3 denotes 101-1000 CG lightning flashes. Category 4 denotes greater than 1000 CG lightning flashes. Average number of thunderstorm days per year at Whiteman AFB taken from Climatic Brief, courtesy of United States Air Force Air Weather Service.

	# OF EVENTS/ # OF AT WHITEMAN AFB					TOTAL #	AVG # TSTM DAYS
PERIOD	1	2	3	4	TOTAL	TSTM DAYS	AT WHITEMAN/YR
MAR-93	0/0	2/1	0/0	1/1	3/2	3/3	3
APR-93	2/0	2/0	1/1	4/4	9/5	8/4	6
MAY-93	4/0	9/2	4/2	2/2	19/6	18/7	9
JUN-93	6/0	6/0	6/3	7/7	25/10	22/12	9
JUL-93	5/0	12/1	7/4	12/11	36/16	25/16	8
AUG-93	3/0	4/1	1/0	5/3	13/4	13/5	8
SEP-93	0/0	3/0	6/4	4/3	13/7	13/7	6
OCT-93	2/0	0/0	1/0	2/2	5/2	3/2	4
NOV-93	1/0	1/0	1/1	0/0	3/1	3/1	2
TOTAL-93	23/0	39/5	27/15	37/33	126/53	108/57	55
MAR-94	1/0	1/0	0/0	1/1	3/1	4/2	3
APR-94	1/0	4/1	4/4	3/3	12/8	13/9	6
MAY-94	0/0	6/1	1/0	2/2	9/3	7/4	9
JUN-94	7/0	6/2	6/4	6/5	25/11	20/11	9
JUL-94	6/0	6/2	8/3	4/4	24/9	18/9	8
AUG-94	1/0	0/0	6/3	7/6	14/9	18/9	8
SEP-94	2/0	2/0	2/1	2/2	8/3	6/3	6
OCT-94	5/0	9/0	0/0	1/1	15/1	11/1	4
NOV-94	1/0	2/0	4/2	0/0	7/2	6/2	2
TOTAL-94	24/0	36/6	31/17	26/24	117/47	103/50	55
TOTAL	47/0	75/11	58/32	63/57	243/100	211/107	110

Table 6. The number of positive cloud-to-ground lightning flashes recorded by the NLDN per month, season, and year for 1989 through 1995. Nearly twice as many positive flashes were detected in 1994 and 1995 as compared to the first four years. Seasons are denoted by spring (March-May), summer (June-August), and fall (September-November).

	YEAR						
PERIOD	1989	1990	1991	1992	1993	1994	1995
JAN	158	57	0	0	2	23	34
FEB	0	11	4	77	10	15	116
MAR	72	205	114	66	90	58	155
APR	9	139	656	370	406	2886	896
MAY	423	1091	901	175	585	303	3416
JUN	184	1933	339	246	1109	1211	1874
JUL	311	479	287	1482	2366	1255	1216
AUG	1033	350	177	187	982	1424	622
SEP	252	42	393	1111	1050	515	321
OCT	265	342	131	94	169	150	179
NOV	0	33	96	441	61	204	78
DEC	0	9	0	2	67	23	1
SPRING	504	1435	1671	611	1081	3247	4467
SUMMER	1528	2762	803	1915	4457	3890	3712
FALL	517	417	620	1646	1280	869	578
TOTAL	2707	4691	3098	4251	6897	8067	8908

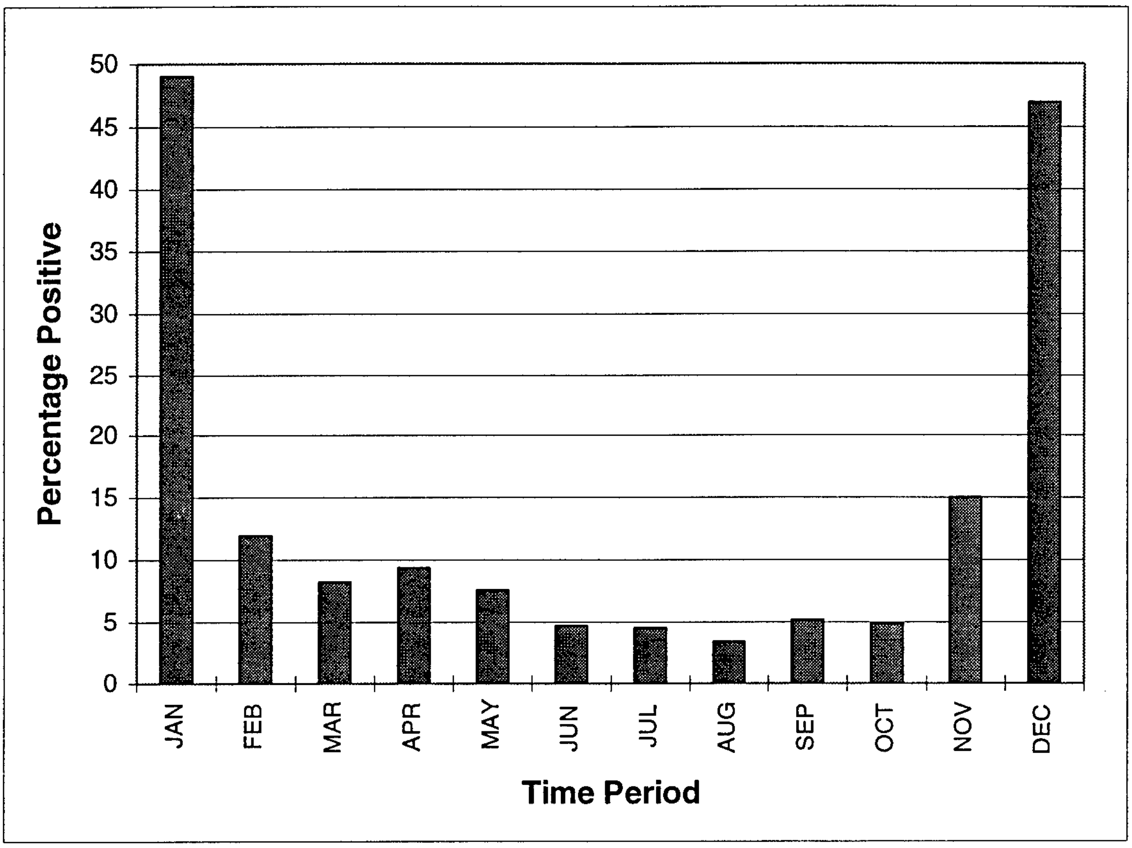

Figure 6. Average monthly percentage of positive cloud-to-ground lightning flashes for the entire period, 1989 through 1995.

monthly percentage of positive lightning for the entire period. January had the highest percentage of positive lightning, but had few flashes overall. Percentages dropped to around 12% for February, and were fairly constant for the spring season with a small peak in April. The lowest percentages were found in the summer, with the smallest percentage for the year in August. Percentages rose again through the fall, with positive lightning percentages in December similar to January. Comparison of this figure to Figure 2, reprinted from Silver's (1995) thesis, reveals that the average percentages and seasonal trends are in good agreement. Although some discrepancy is seen in comparisons of January and December, this is due to the fact that Silver's study includes all of the United States. His wintertime averages are heavily influenced by flashes recorded in the South, and especially Florida, where the percentage of positive lightning is low (Orville, 1994).

Figure 7 displays the percent positive lightning flashes by month and year during the spring season. The percentage of positive lightning for each season is shown in the last column of the graph. The overall average for each month and for the entire season is displayed as the last bar in each column. March showed a high variability between months. However, it also had the smallest sample size, and was easily influenced by individual storms. One storm that passed over the region in March 1990 produced well over half of all flashes for that month, and the percentage of positive flashes throughout this storm was over 25%.

April showed the largest variability of the three months, although the high percentage of positive lightning for 1990 was again influenced by the small amount of flashes recorded that month (see Table 1). On the other hand, neither 1994 nor 1995 were influenced by individual storms or a small sample size. In fact, April 1994 began a trend in which percent positive lightning for each month during the warm season (except May 1994) were much higher than in previous years. Finally, the month of May was very steady except for 1995, which had a percentage more than twice as high as any other year.

Figure 8 is a graph of percentage positive flashes for the summer season. Once again, the high percentage of positive flashes seen in June 1992 was probably the result of the low number of lightning flashes recorded that year, only about 13% of normal. The high percentage for June 1995 was out of a total of over 19 000 flashes, about the normal

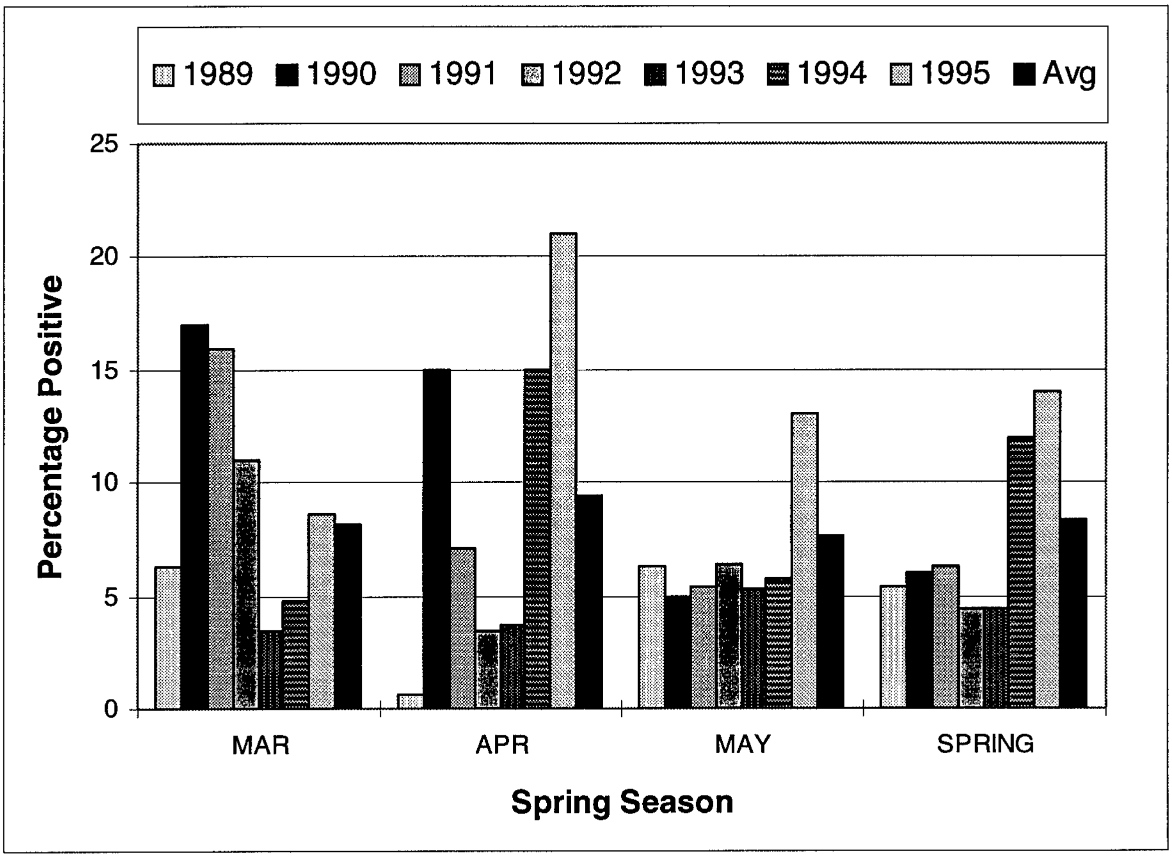

Figure 7. Monthly percentage of positive cloud-to-ground lightning flashes for the spring season from 1989 through 1995, and the overall monthly average. Seasonal percentage and average is included as well.

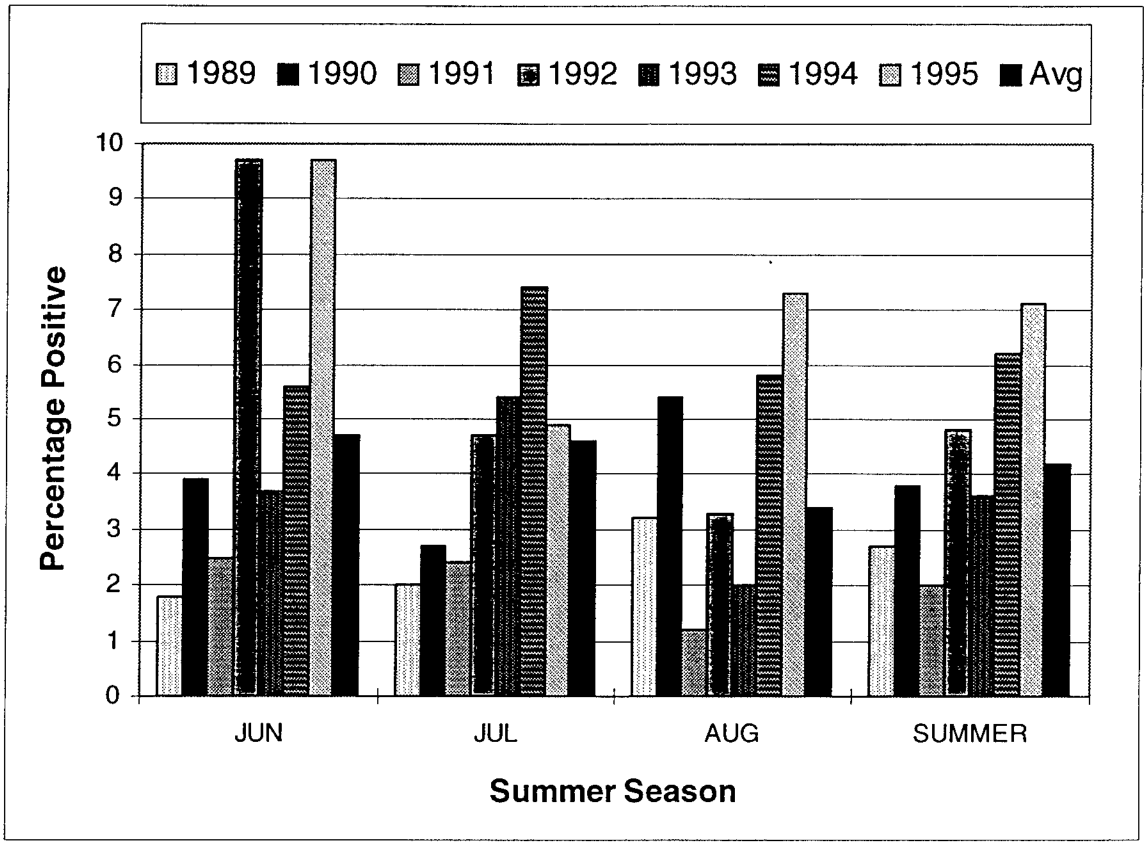

Figure 8. Monthly percentage of positive cloud-to-ground lightning flashes for the summer season from 1989 through 1995, and the overall monthly average. Seasonal percentage and average is included as well.

average. The summer average of 4.2% is very close to the Reap and MacGorman (1989) estimate that 4.33% of all warm season CG flashes for the central United States are positive. Both 1994 and 1995 summer seasonal percentages were much higher than the average over the seven year period. The highest percentages of positive flashes were recorded in 1995 for two of the three months and in 1994 for the other month.

The percentage of positive flashes for the fall season are seen in Figure 9. The trend towards higher percentages of positive lightning continued in September 1994, and then ended abruptly. Overall, the distribution of positive lightning percentages was fairly even for the fall season, with the exception of 1994. The unusually high value for November 1991 was due to a single storm that started out positively dominated, and contained high amounts of positive lightning throughout it's history.

Due to the small number of thunderstorms during the winter months, few flashes were recorded in the study area. Of the flashes that were recorded, about 23% were of positive polarity. However, about 40% of all flashes recorded during December, January, and February from 1989 through 1995 occurred in one storm in February 1995. Only about 11% of those flashes were positive. Subtracting this month out showed that on average, about 31% of wintertime flashes were positive.

Finally, Figure 10 shows the yearly average of percentage positive lightning flashes for each of the seven years and the total average for the entire period. The overall average percentage of positive lightning in a given year was 5.4%. It is easily seen that 1994 and 1995 had percentages of positive lightning almost double that of any other year. This is another indication that the detection efficiency of the NLDN has increased.

While the distribution of lightning per day and per event varied greatly, the diurnal distribution of CG lightning was more consistent. Figure 11 shows the total number of flashes versus time of day for the total period 1989 through 1995. Although lightning flashes were possible at any time of day, a distinct minimum of activity was observed around 1500-1600 UTC. A sharp rise in activity was evident until the peak in flashes was reached at 2200 UTC. The activity then subsided to a slight minimum at 0200 UTC, before increasing again to a secondary maximum at 0500 UTC. The lightning activity then slowly declined until 1000 UTC, when the decrease became steeper until reaching the mid-

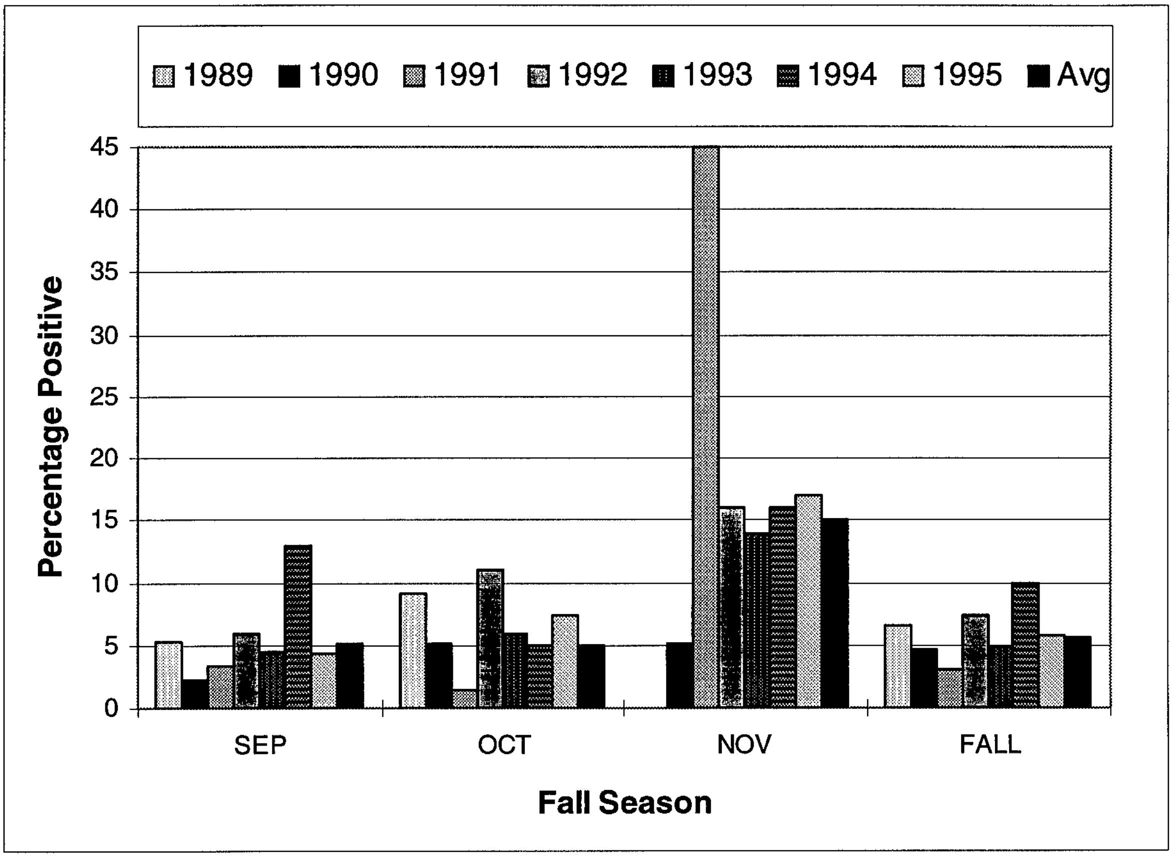

Figure 9. Monthly percentage of positive cloud-to-ground lightning flashes for the fall season from 1989 through 1995, and the overall monthly average. Seasonal percentage and average is included as well. The high percentage of positive lightning in November 1990 was due to a single storm.

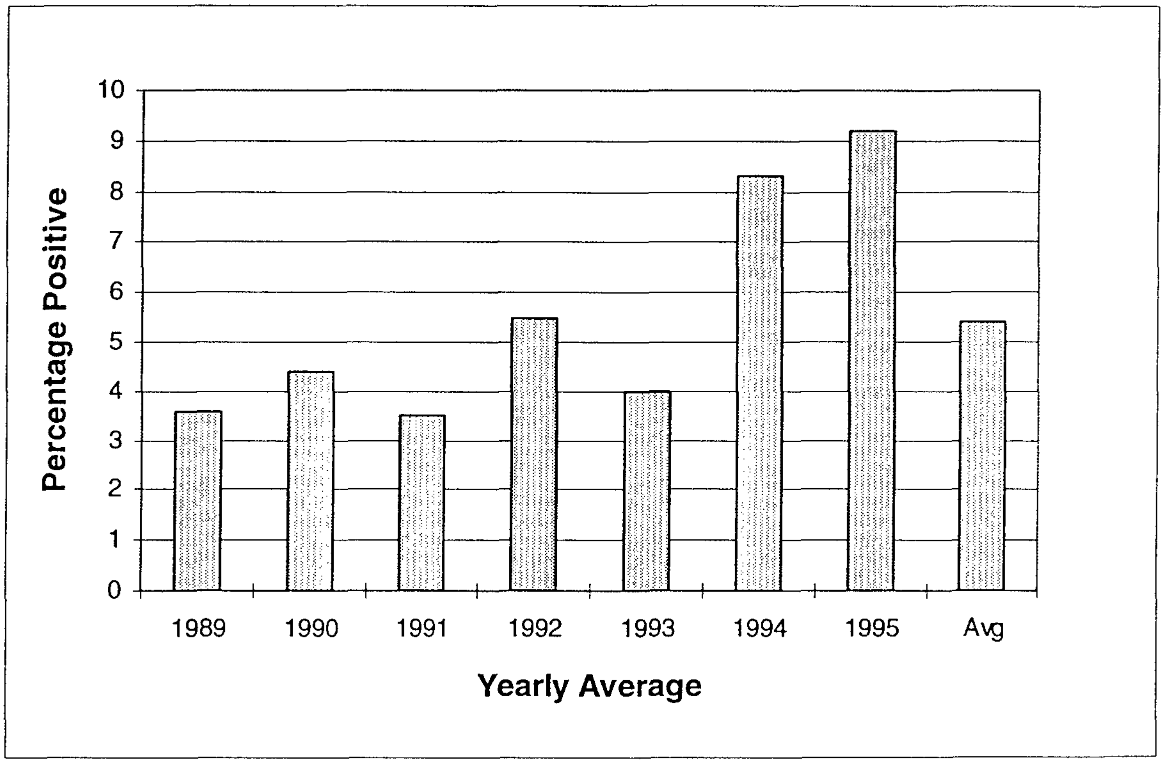

Figure 10. Yearly average of percentage positive cloud-to-ground lightning flashes from 1989 through 1995, and the overall percentage for the period. The percentage of positive flashes for 1994 and 1995 was almost double the percentages for the first 5 years.

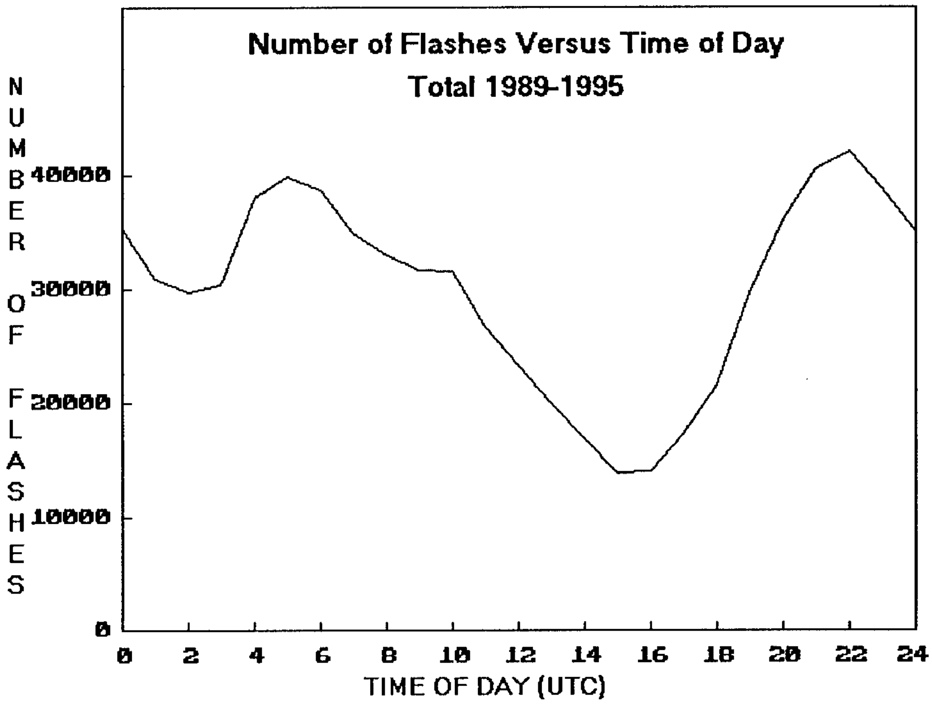

Figure 11. Number of lightning flashes versus time of day for the total period 1989 through 1995. Subtract 6 hours for Central Standard Time. Maximum activity is observed in late afternoon and near midnight local time.

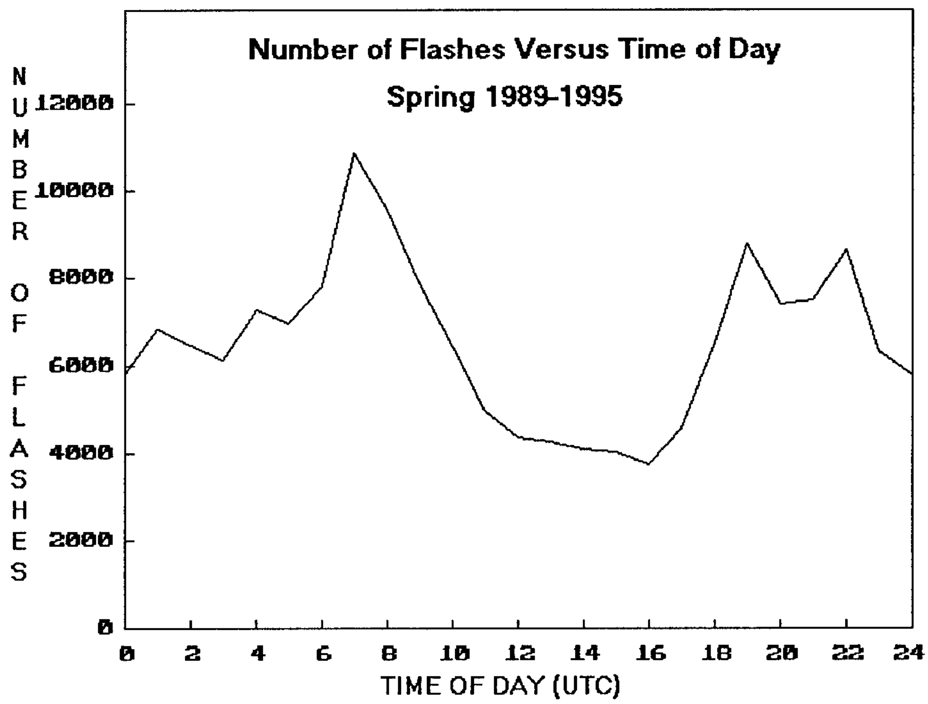

Figure 12. Same as Figure 11, except for the spring period (March-May) of 1989 through 1995. Nocturnal maximum is apparent.

morning minimum.

To see if the diurnal distribution of CG lightning flashes varied over different parts of the year, the number of flashes were compared to the time of day on a seasonal basis. Figure 12 is a graph of the number of flashes versus time of day during the spring period. Figure 13 is a graph of the number of flashes versus time of day during the summer period. Figure 14 is a graph of the number of flashes versus time of day during the fall period. For the spring period, a bimodal distribution was apparent, with a maximum in activity at 0700 UTC which fell rapidly to a broad minimum from 1200-1600 UTC. Flash activity then increased to smaller maximums at 1900 and 2200 UTC, with another secondary minimum from 0000-0500 UTC.

As stated earlier, almost two-thirds of all lightning flashes recorded in the seven year period occurred during the summer. Not surprisingly then, the summer diurnal pattern was very similar to the total diurnal distribution. The major difference is that the peak at 0500 UTC was more pronounced and is actually higher than the 2200 UTC peak.

Finally, the fall period showed a peak in activity at 0000 UTC, which fell rapidly between 0200-0300 UTC, then experienced an erratic decline until 1800 UTC. A sharp increase in activity was noticeable until 2100 UTC, before remaining almost steady until the sharp increase from 2300-0000 UTC.

The diurnal distributions of first and last flashes of each event were examined to determine favored start and end times of thunderstorm activity. Histograms for first and last flashes of all thunderstorm events for the spring, summer, fall, and total period were developed. Similarly, to see if there are preferred times of more organized convective events, histograms were also developed for first and last flashes of all category 3 and 4 thunderstorm events only. All charts show the number of first and last lightning flashes that occurred within 3 hour time blocks.

Overall, the first flash of lightning, signaling the beginning of thunderstorm activity, is possible at any time of day (Fig. 15a). Nevertheless, the chances of activity beginning were slightly lower in the early morning (1200-1500 UTC), and substantially higher in the middle and late afternoon (1800-0000 UTC). The graph of last flash (Fig. 15b) reveals a slight preference for late afternoon and early evening (2100-0200 UTC), as

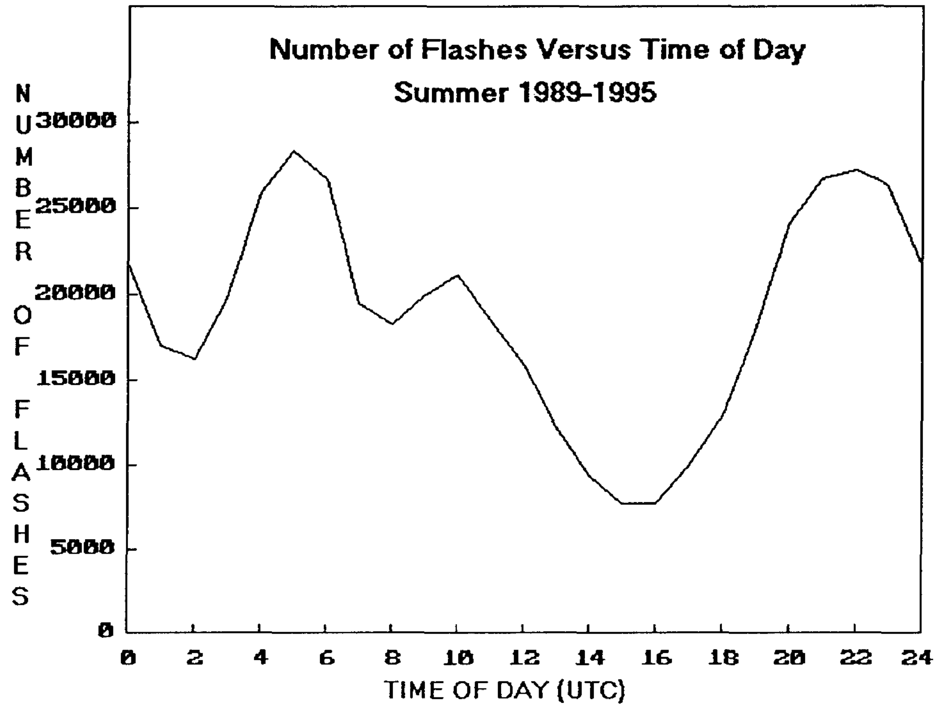

Figure 13. Number of lightning flashes versus time of day during the summer period (June-August) of 1989 through 1995. Subtract 6 hours for Central Standard Time. Maximum activity is observed in late afternoon and near midnight local time.

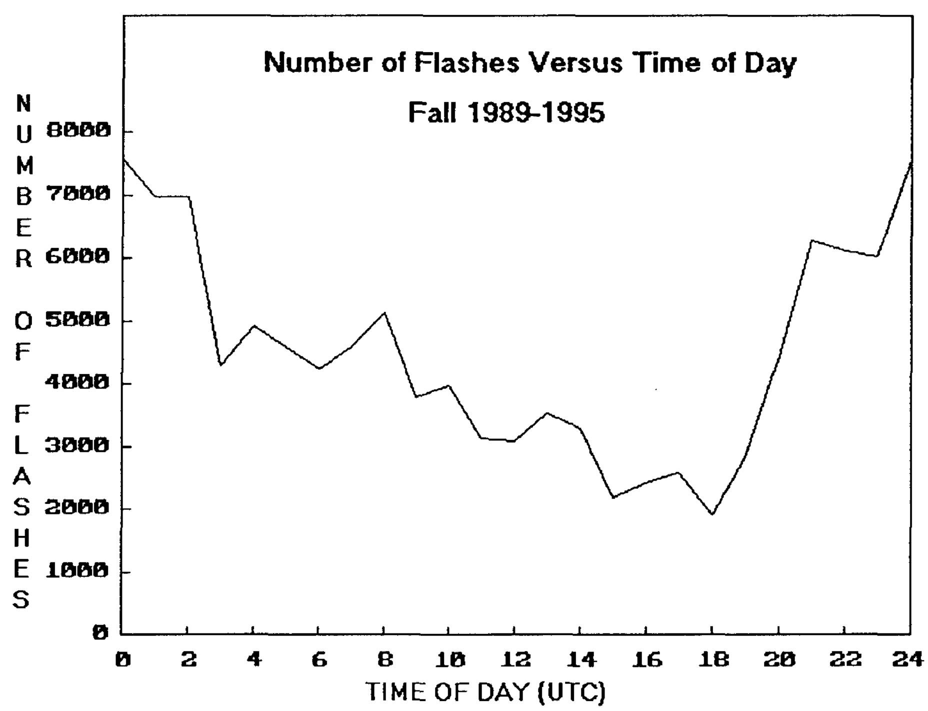

Figure 14. Same as Figure 13, except for the fall period (September-November) of 1989 through 1995. Nocturnal maximum has disappeared.

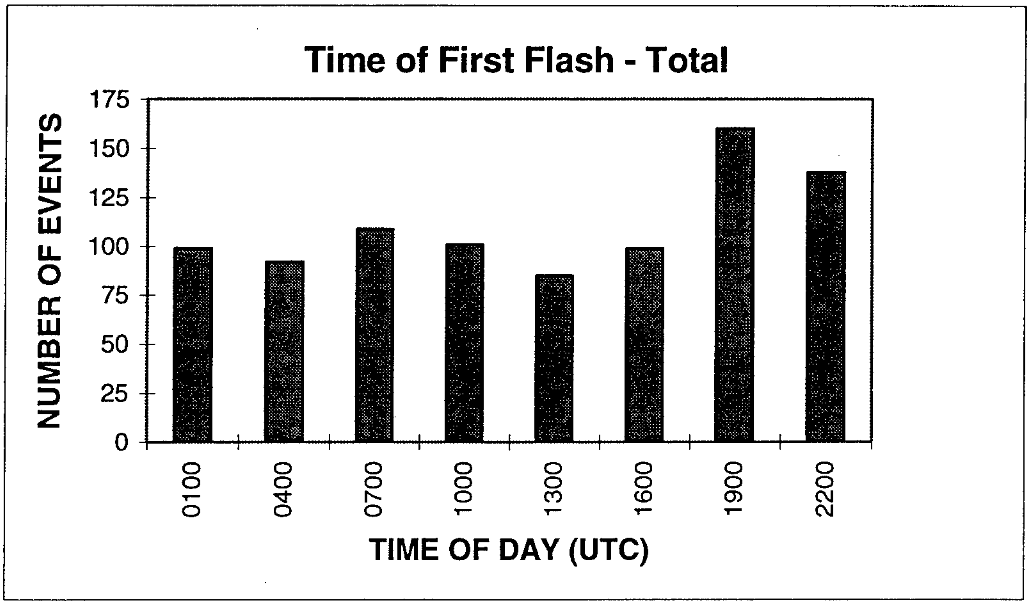

Figure 15a. Time of first cloud-to-ground lightning flash in three hour blocks of all thunderstorm events during the total period, 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc. First flash was possible at any time of day, with a slight preference in the late afternoon local time.

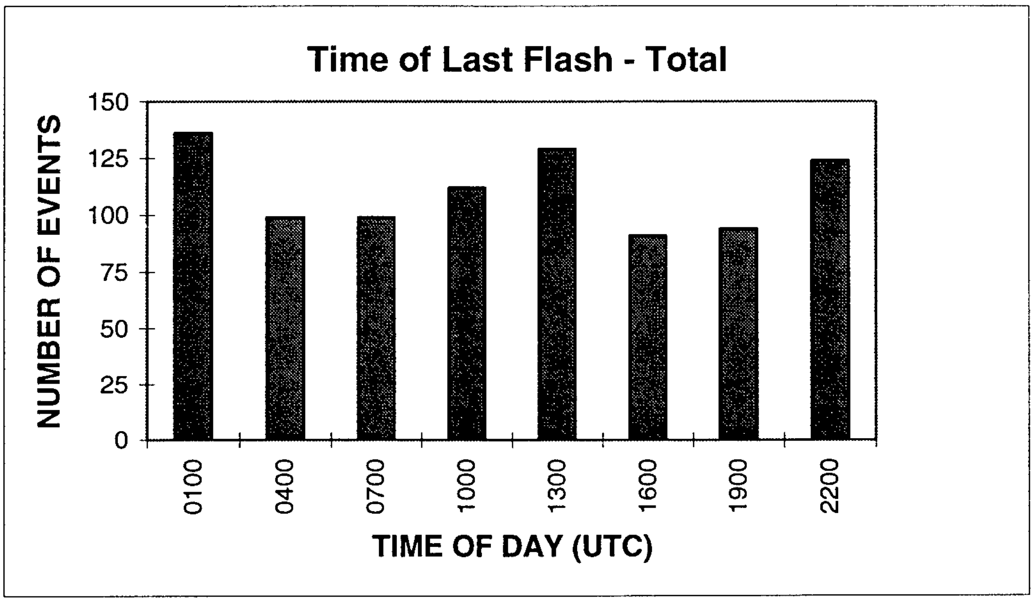

Figure 15b. Same as Figure 15a, except for last flash. A slight preference was seen for the early morning and early evening.

well as early morning (1200-1400 UTC). Looking at category 3 and 4 events only, a preferred time of first flash was much more distinguishable at 1800-2000 UTC (Fig. 16a), with a minimum time of 1200-1400 UTC. Figure 16b shows that favored last flash times were early evening (0000-0300 UTC) and early morning (1200-1400). The mean length of time from first to last flash in the study area for all category 3 and 4 events for the entire 7 year period was 8.9 hours.

A breakdown of first and last flash times by season was more useful and specific. The first lightning flashes during the spring tended to occur in a broad time from mid-afternoon to early evening, with a peak around 2200 UTC (Fig. 17a). A smaller peak also occurred between 0600-0900 UTC. First flashes were least likely from 0900-1600 UTC. The last lightning flashes during the spring tended to occur in the late afternoon and early evening, mostly between 2000-0300 UTC (Fig. 17b). A smaller peak was seen from 0900-1200 UTC. Both peaks corresponded well to the peaks in first flash activity, except they followed about 2-4 hours later. For more organized convection, first flashes tended to occur evenly during most of the day, although the fewest cases occurred from 0900-1600 UTC (Fig. 18a). No favorable trends were found in last flash times as well, although a minimum in last flashes was observed from 1600-2000 UTC (Fig. 18b). The mean length of time that flashes were observed in the study area for all category 3 and 4 events during the spring period was 8.7 hours.

Not surprisingly, lightning flashes during the summer usually began in the mid-afternoon, with a large peak in first flashes from 1800-2100 UTC (Fig. 19a). Otherwise, first flash activity remained fairly consistent throughout the rest of the day, with the exceptions of a small minimum between 1200-1500 UTC and a temporary increase in activity between 0900-1200 UTC. Lightning flashes tended to end in the late afternoon and early evening, generally between 2100-0200 UTC (Fig. 19b). The peak in last flashes, however, occurred between 1200-1500 UTC. Again these peaks corresponded fairly well to the peaks in first flash activity, with a delay of 3-5 hours. Figures 20a and 20b show the first and last flash times, respectively, for category 3 and 4 thunderstorm events. Again, while first flashes tended to occur at any time, the peak of activity was between 1800-2100 UTC. Two peaks of last flash times were evident, with a maximum peak

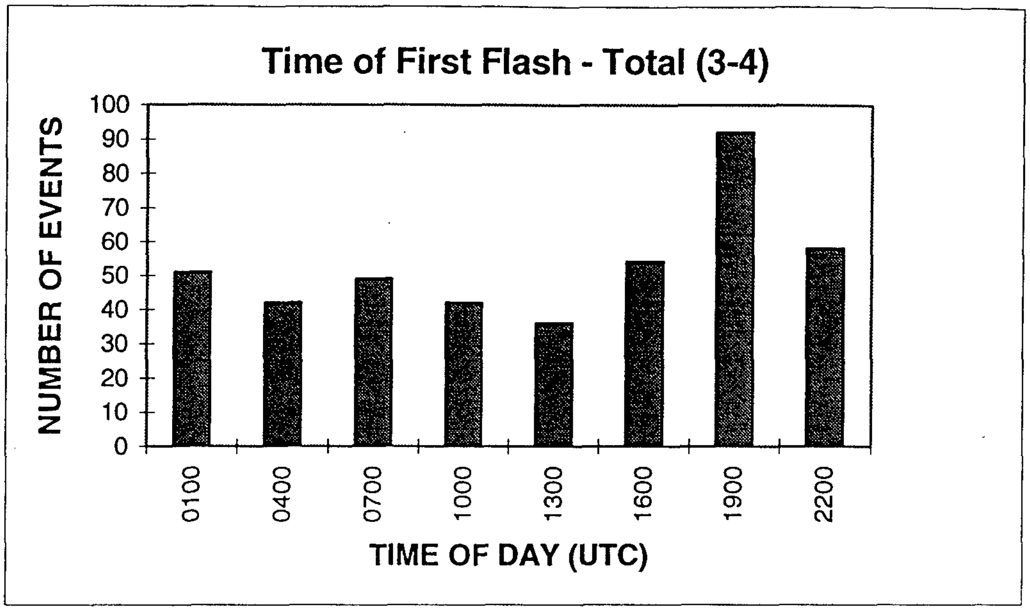

Figure 16a. Time of first cloud-to-ground lightning flash in three hour blocks of all category 3 and 4 (greater than 100 total flashes) thunderstorm events during the total period, 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc. A preference was observed for the late afternoon local time.

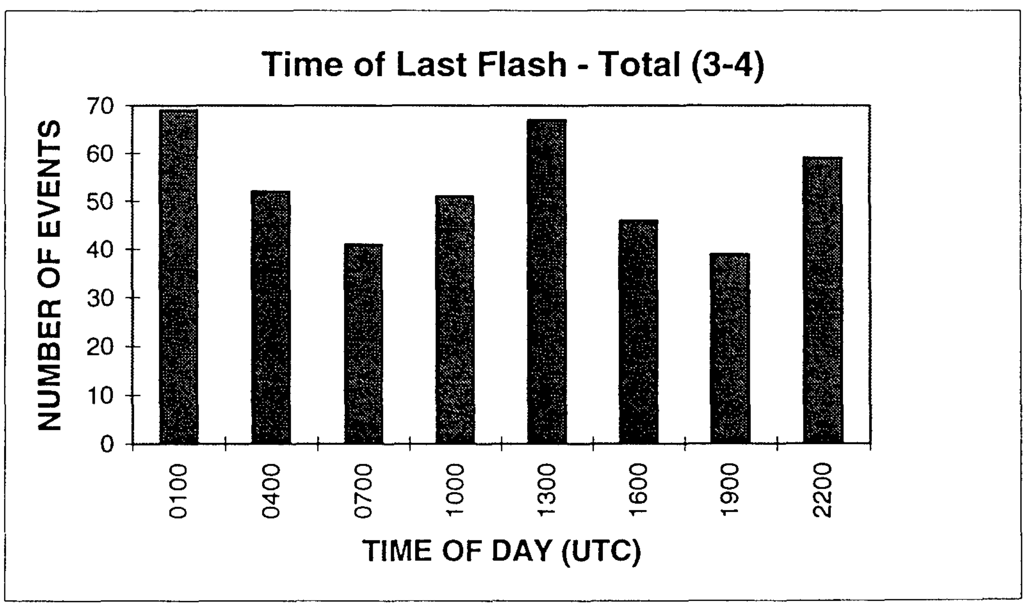

Figure 16b. Same as Figure 16a, except for last flash.

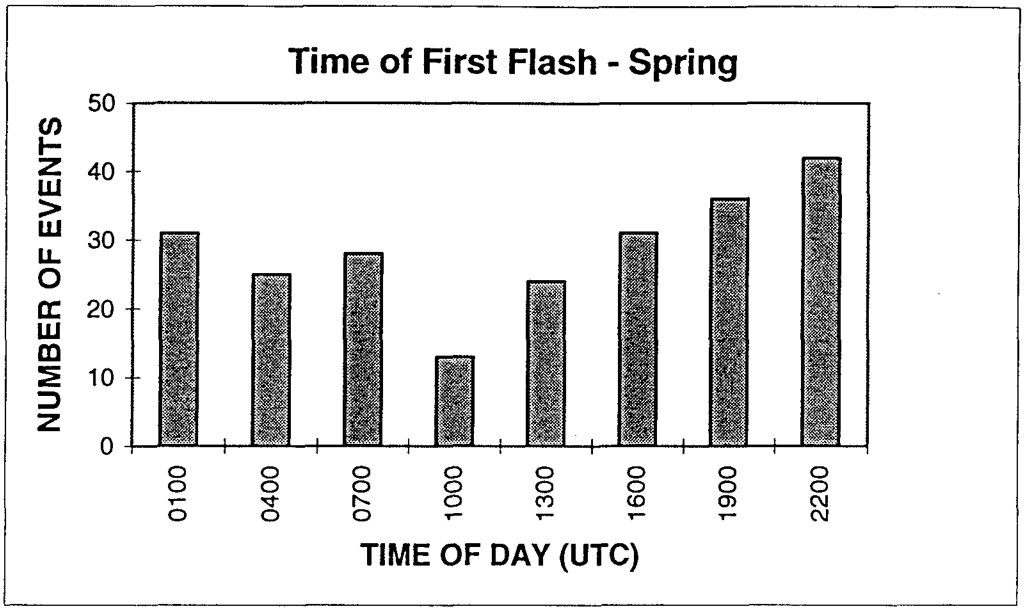

Figure 17a. Time of first cloud-to-ground lightning flash in three hour blocks of all thunderstorm events during the spring period (March-May) for 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc. First flash frequency peaked in the late afternoon local time.

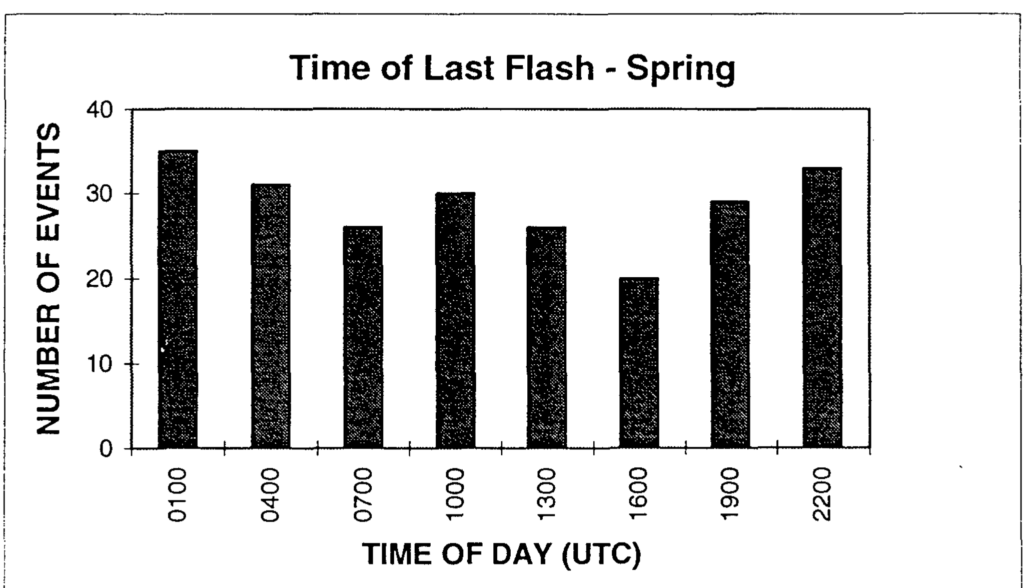

Figure 17b. Same as Figure 17a, except for last flash. Last flash was possible at any time.

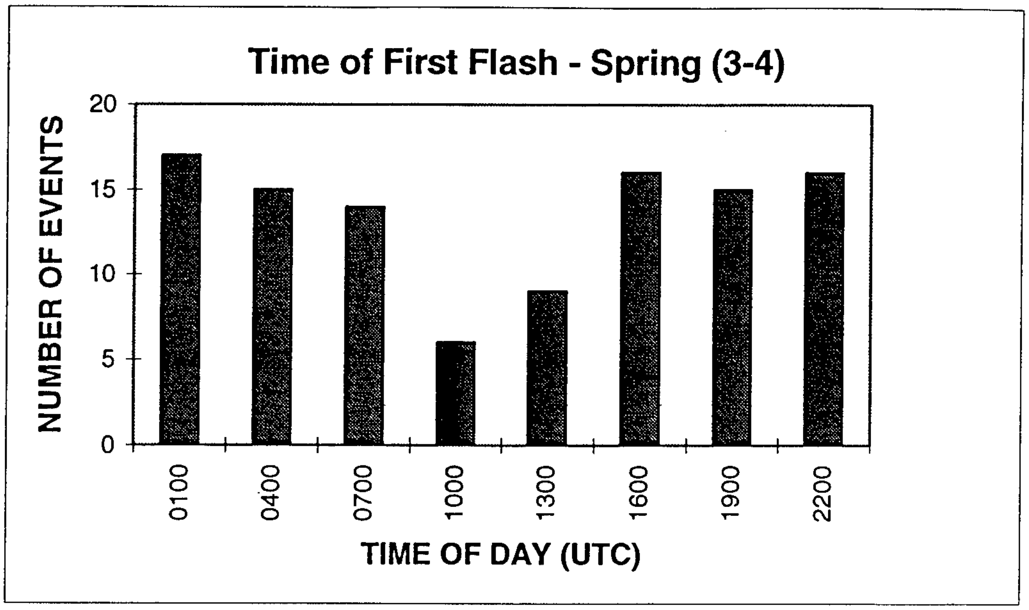

Figure 18a. Time of first cloud-to-ground lightning flash in three hour blocks of all category 3 and 4 (greater than 100 total flashes) thunderstorm events during the spring period (March-May) for 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc. A minimum in first flash time was observed in the early morning.

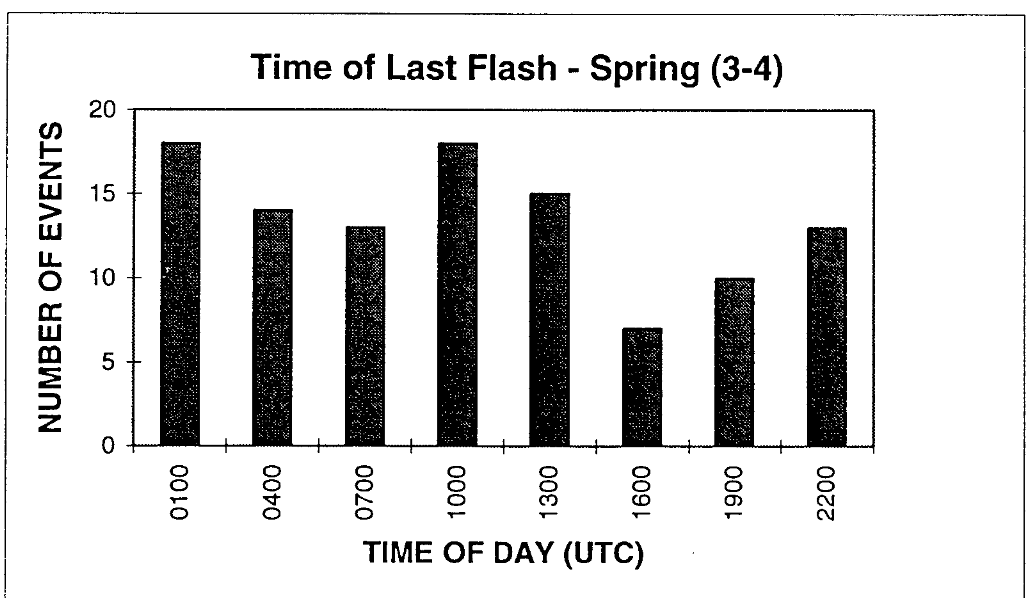

Figure 18b. Same as Figure 18a, except for last flash.

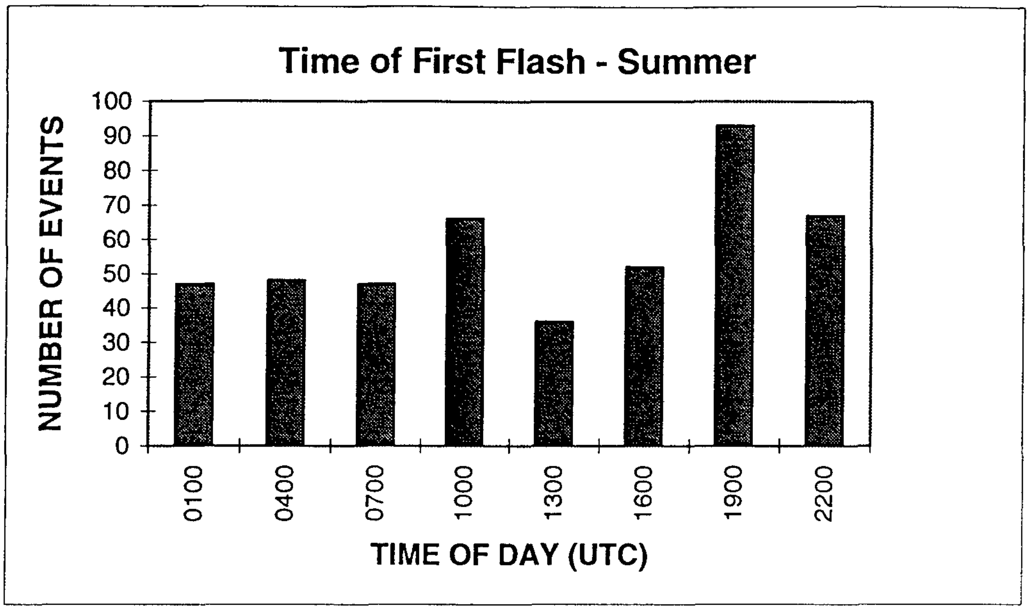

Figure 19a. Time of first cloud-to-ground lightning flash in three hour blocks of all thunderstorm events during the summer period (June-August) for 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc.

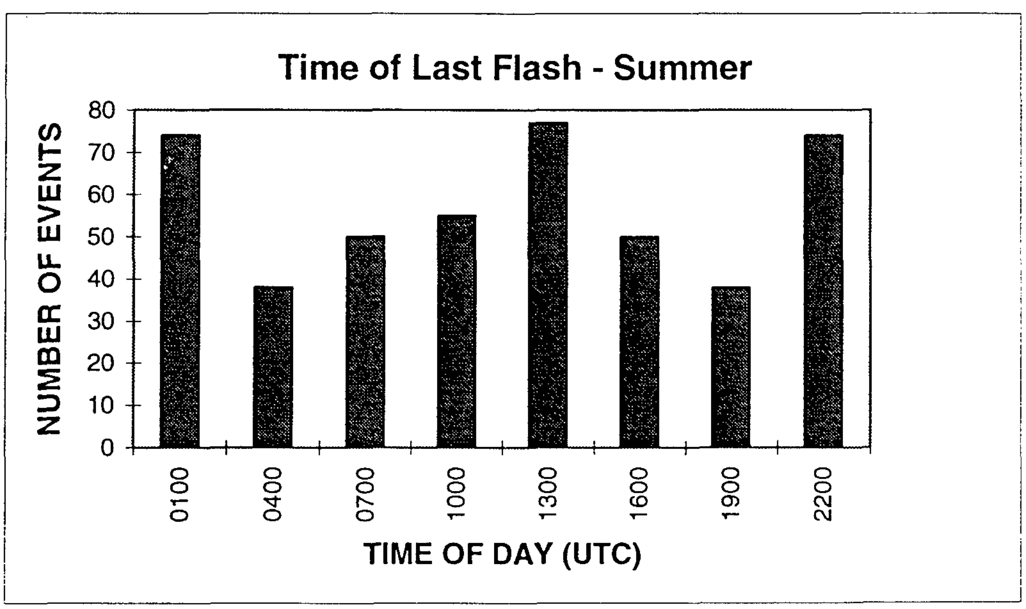

Figure 19b. Same as Figure 19a, except for last flash.

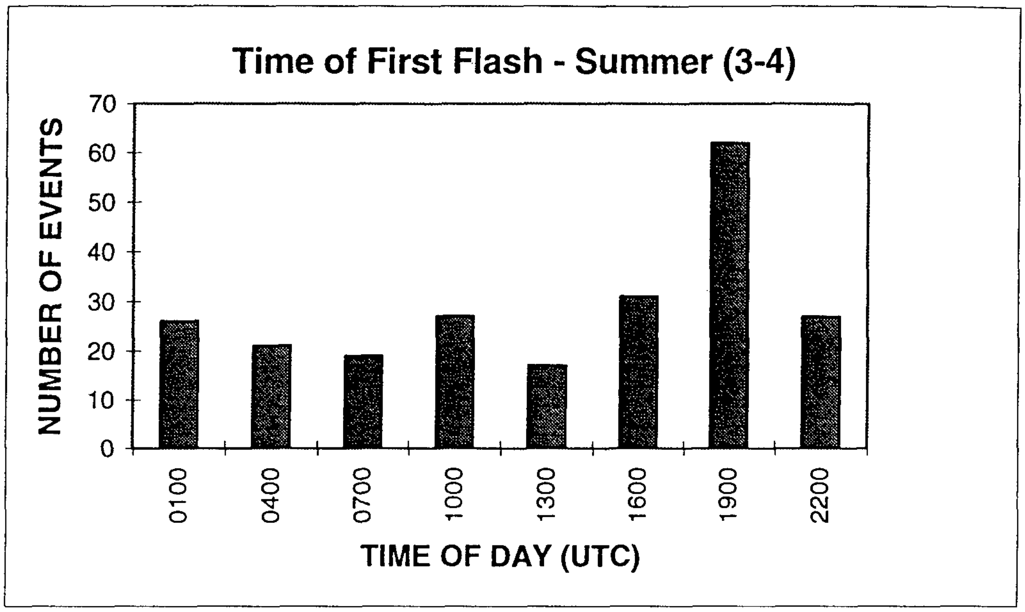

Figure 20a. Time of first cloud-to-ground lightning flash in three hour blocks of all category 3 and 4 (greater than 100 total flashes) thunderstorm events during the summer period (June-August) for 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc. A pronounced peak was seen during the late afternoon.

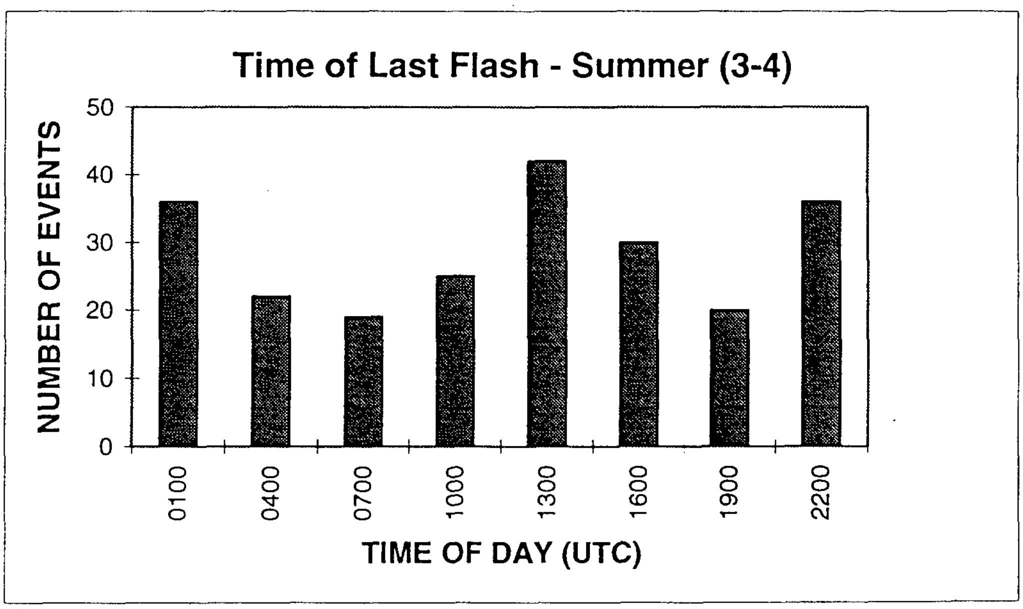

Figure 20b. Same as Figure 20a, except for last flash. Preferred times were the early evening and early morning hours locally.

between 1200-1400 UTC and a broad secondary peak from 2100-0200 UTC. The mean length of time that flashes were observed in the study area for all category 3 and 4 events during the summer period was 9.7 hours.

During the fall, a late afternoon and overnight maximum was apparent (Fig. 21a). A peak was found between 0600-0900 UTC, with activity decreasing steadily until a sharp increase at 1800-2100 UTC. Then a similar decrease was seen until a sharp rise back to the nighttime peak. Inspection of the graph for last flash times (Fig. 21b) reveals that times were about evenly spread out with no real trends. Starting times for category 3 and 4 events indicate preferred times of late afternoon and overnight (Fig. 22a). Hourly data (not shown) gave preferred times from 1900-0000 UTC and another period from 0600-1000 UTC. A minimum in starting times was found between 1000-1900 UTC. Last flashes tended to take place between 0000-0600 UTC, and were spread out evenly otherwise (Fig. 22b). The mean length of time that flashes occur in the study area for all category 3 and 4 events during the fall period was 8.6 hours.

A diurnal pattern was evident for flashes of positive polarity as well. Figure 23 shows the number of positive flashes versus time of day for the seven year period. A peak in the number of flashes was seen at 0600 UTC (midnight CST), which erratically decreased to a minimum between 1600-1800 UTC. The number of positive flashes quickly increased to a smaller peak at 0000 UTC, with a small decrease again at 0200 UTC. While the diurnal pattern of positive flashes was similar in shape to the pattern for total flashes seen in Figure 11, it lagged behind the total flash trend by 1-2 hours.

Positive flashes were separated by season and again compared versus time of day. Figures 24, 25, and 26 are the graphs of positive lightning flashes versus time of day for the spring, summer, and fall seasons, respectively. For the spring and summer periods, the graphs of positive flashes are almost a mirror image of the total flash graphs. The fall season graph of positive flashes is similar to its total flash graph as well, but the amplitude of the positive flash peaks was much stronger than for the total flash peaks. In all three cases, the peaks and valleys for each season lagged behind their corresponding maximum or minimum in total flashes by 1-2 hours.

The time of sharpest decline, after the largest peak in positive lightning flashes for

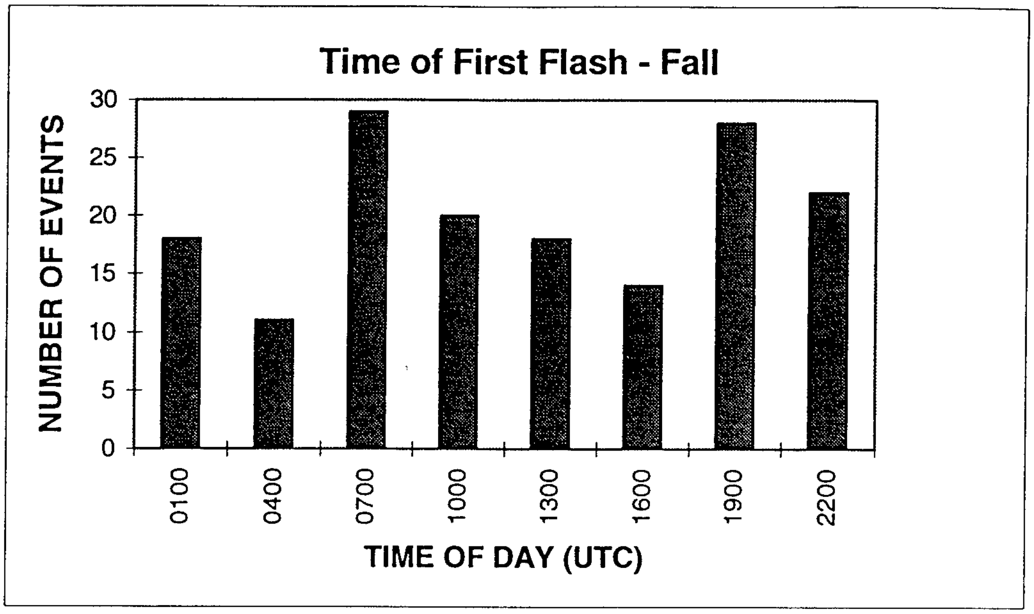

Figure 21a. Time of first cloud-to-ground lightning flash in three hour blocks of all thunderstorm events during the fall period (September-November) for 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc.

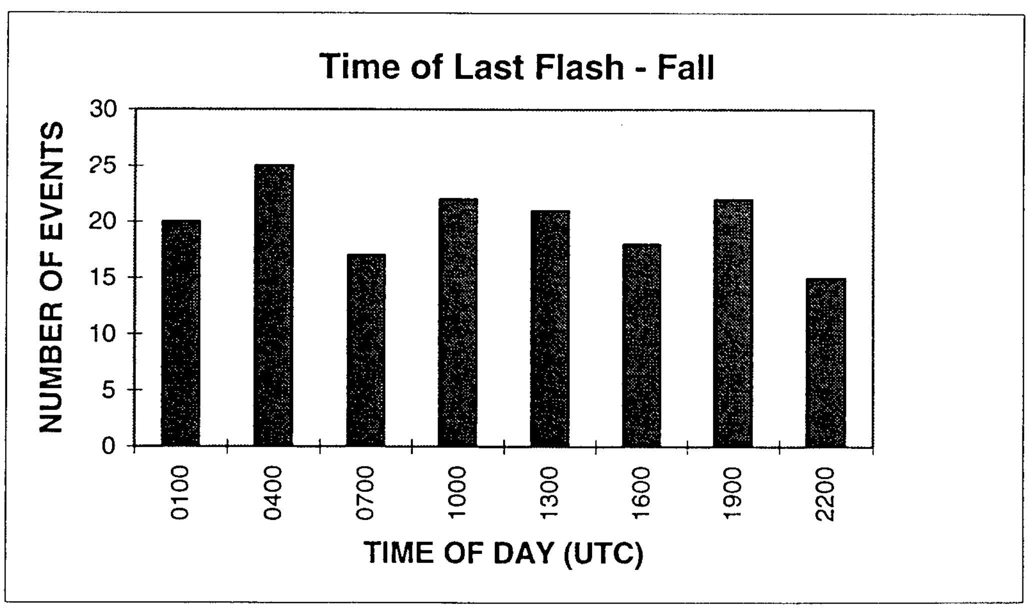

Figure 21b. Same as Figure 21a, except for last flash.

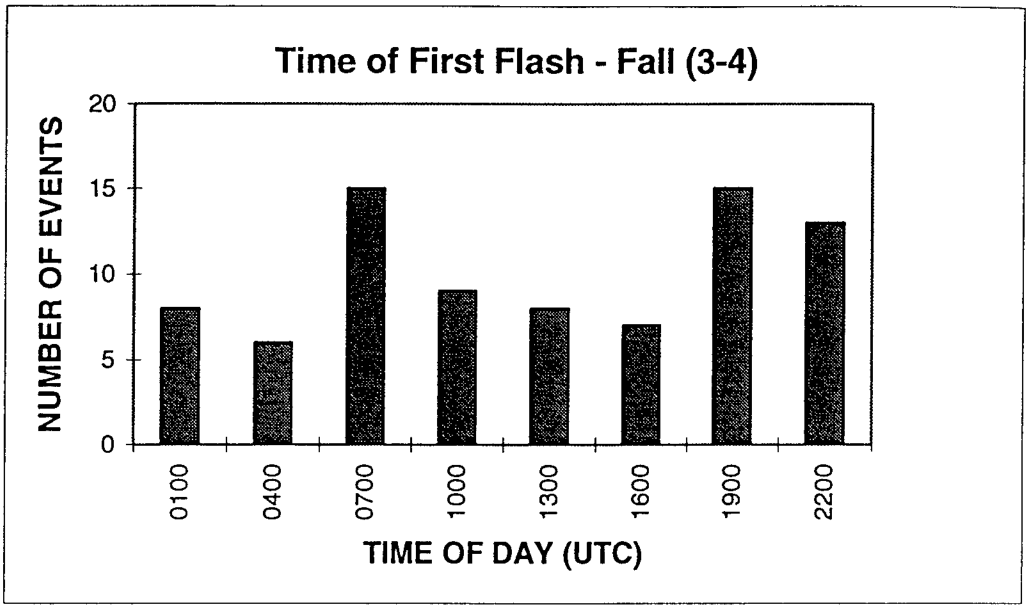

Figure 22a. Time of first cloud-to-ground lightning flash in three hour blocks of all category 3 and 4 (greater than 100 total flashes) thunderstorm events during the fall period (September-November) for 1989 through 1995. Times shown are the midpoint of the block. For example, 0100 represents the block of time from 0000-0259:59 UTC, 0400 represents the block of time from 0300-0559:59 UTC, etc.

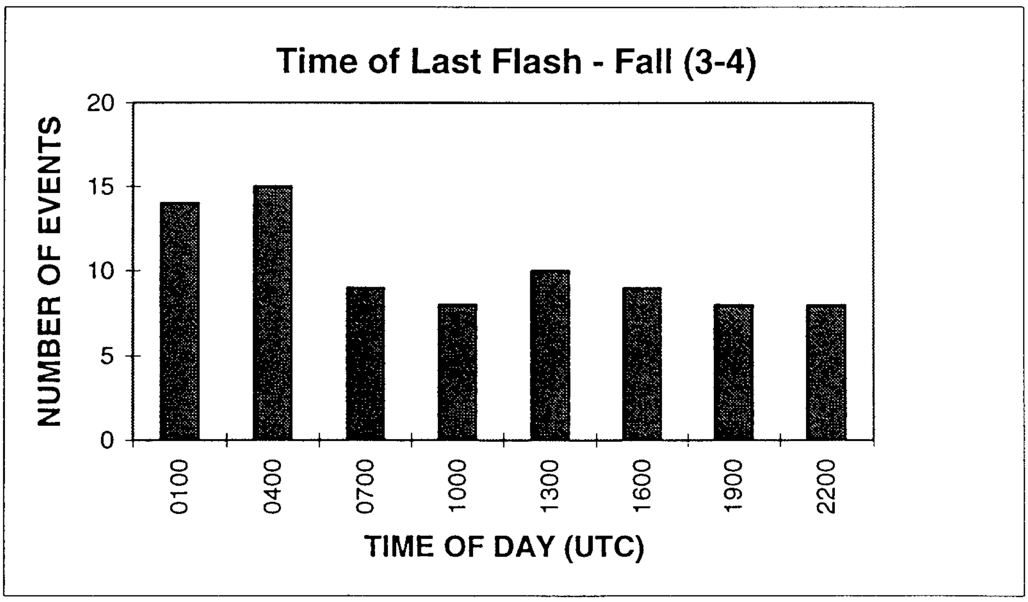

Figure 22b. Same as Figure 22a, except for last flash.

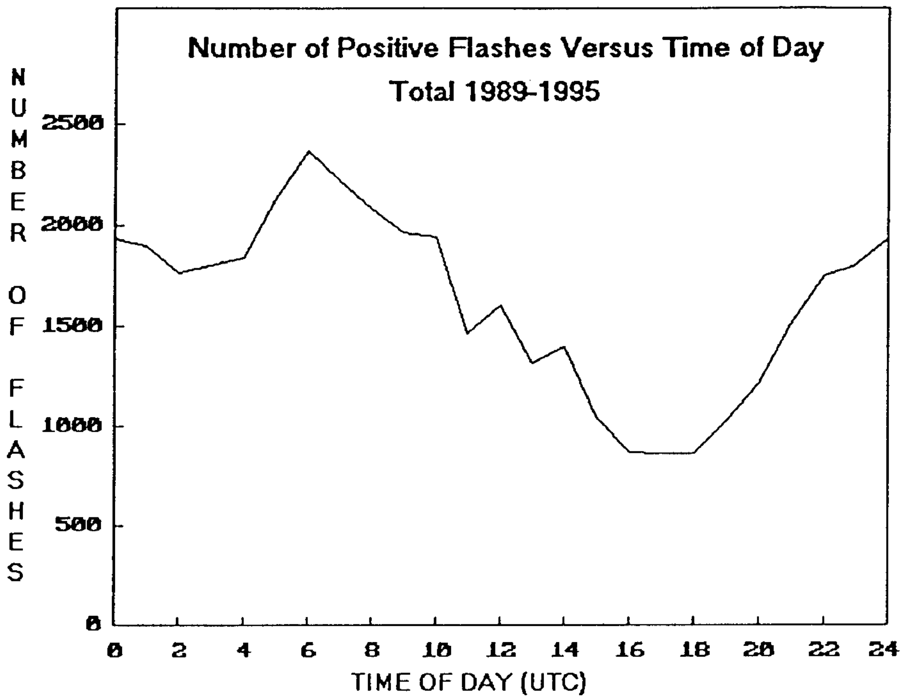

Figure 23. Number of positive lightning flashes versus time of day for the total period 1989 through 1995. Subtract 6 hours for Central Standard Time. Peaks in activity lag those of all flashes by 1-2 hours.

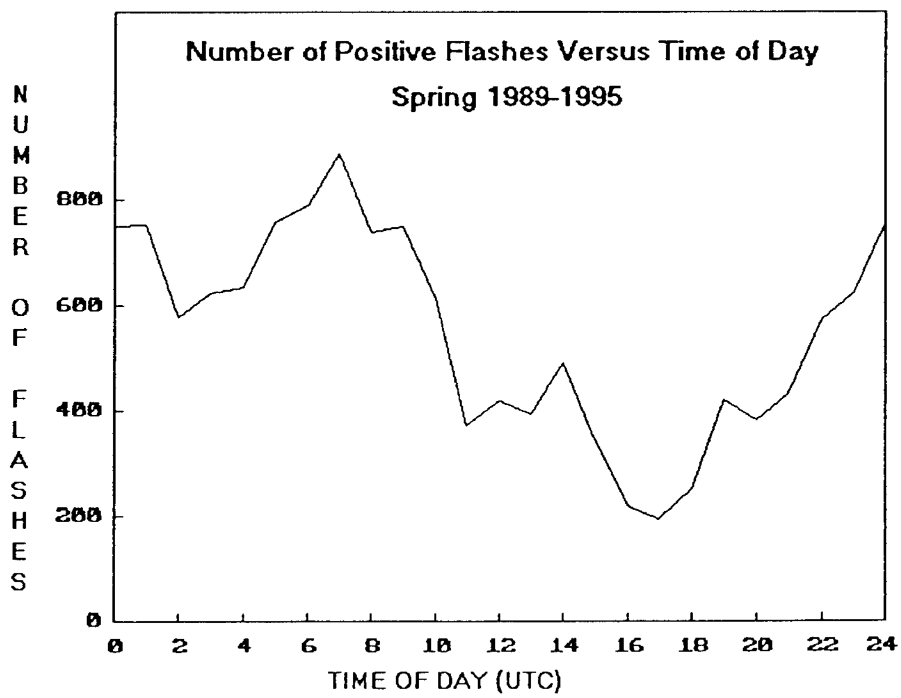

Figure 24. Same as Figure 23, except for the spring period (March-May) of 1989 through 1995. Maximum activity in early evening and overnight local time.

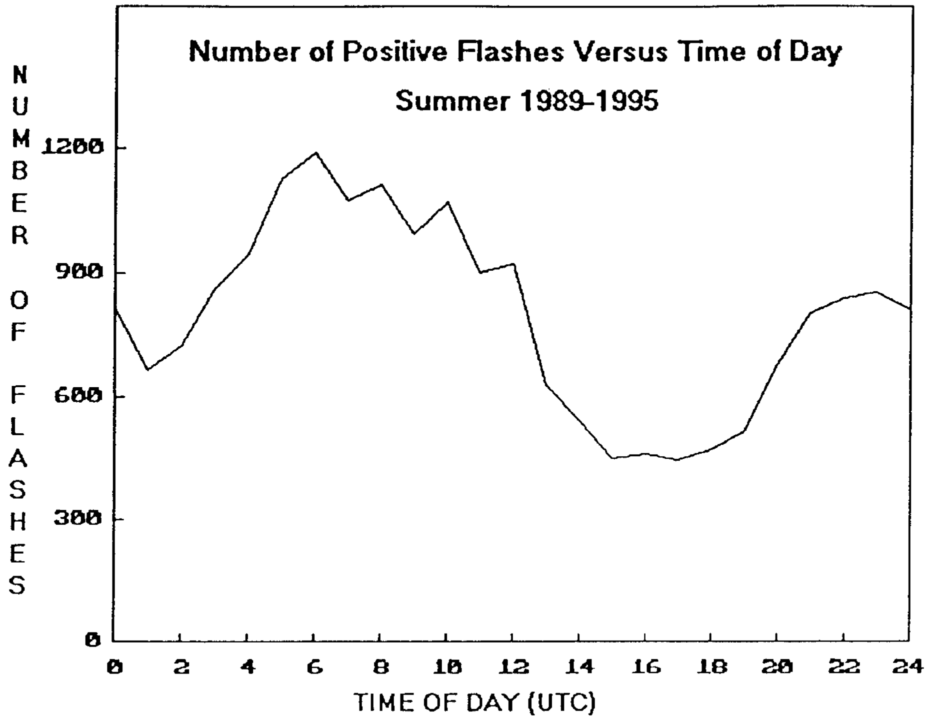

Figure 25. Number of positive lightning flashes versus time of day during the summer period (June-August) of 1989 through 1995. Subtract 6 hours for Central Standard Time. A midnight local time maximum is apparent.

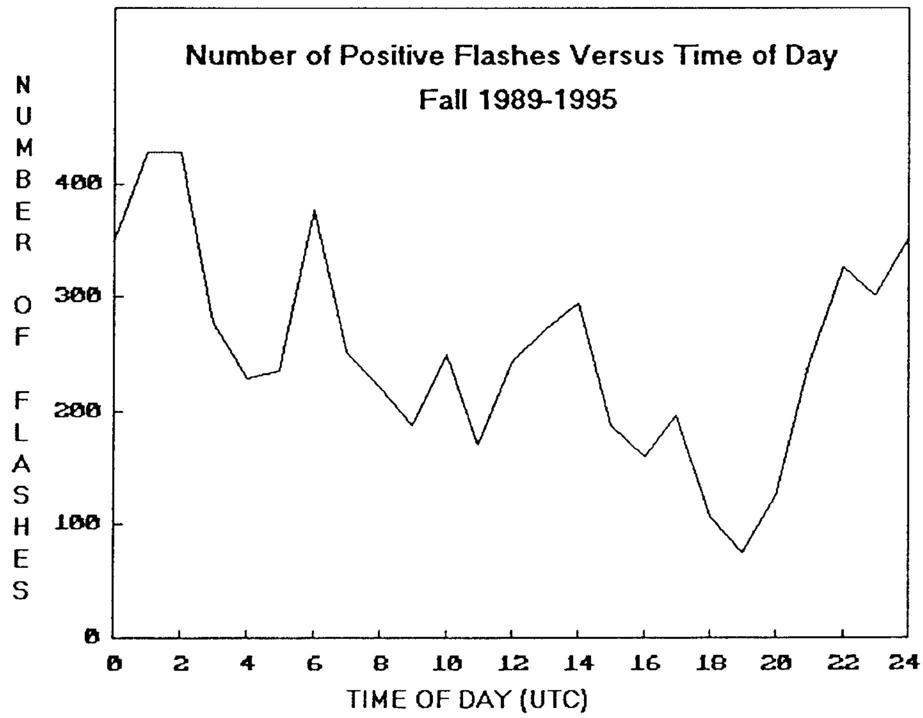

Figure 26. Same as Figure 25, except for the fall period (September-November) of 1989 through 1995. An early evening maximum, early afternoon minimum are apparent.

each season, coincided with the time of the largest number of last flash events for that respective season. The decline in positive flashes between 0900 UTC and 1100 UTC during the spring season corresponded to the maximum number of last flash events seen from 0900-1100 UTC in Figure 18b. Similarly, the drop in positive flashes from 1200-1400 UTC for the summer season corresponded to the maximum number of last flash events between 1200 UTC and 1400 UTC (Fig. 20b). Finally, the sharp decline from 0200-0400 UTC for the fall season compared favorably with the peak from 0300-0500 UTC of last flash events in Figure 22b. The lag in peak times between total flashes and positive flashes, and the correlation of declines in positive flashes after these peaks to the maximum number of last flash events per time period, shows that the highest amount of positive lightning was located in the stratiform region of thunderstorms.

Finally, Figure 27 shows the percentage of all positive flashes versus time of day for the entire 7 year period. Interestingly, there did seem to be a diurnal effect on the percentage of positive lightning. A distinct minimum was seen at 2000 UTC, with a maximum peak at 1400 UTC. Figures 28, 29, and 30 show the percentage of positive lightning versus time of day for the spring, summer, and fall seasons, respectively. In all three cases, the minimum in percentage of positive lightning was found around 2000 UTC, which is early to mid-afternoon, local time. A peak was seen during all three seasons around 1400 UTC as well, although other maxima occurred during each season. No explanation is given for this phenomenon.

b. Spatial distribution and variability

The distribution and variability of CG lightning flashes can be described on a spatial scale as well as a temporal scale. The number of lightning strikes in a given area is referred to as the ground flash density (GFD). The GFD can be described on both a seasonal and yearly basis. The average GFD for the spring period is shown in Figure 31. The flashes per square kilometer are fairly low, with maximum values between 1.5-2.5 flashes km^{-2} located to the west and southeast of Whiteman AFB, and another near the southeast corner of the region. The top one-fourth of the box is an area of minimum values between 0.6-1.0 flashes km^{-2}.

For the summer period, the pattern of GFD over the region was reversed (Fig. 32).

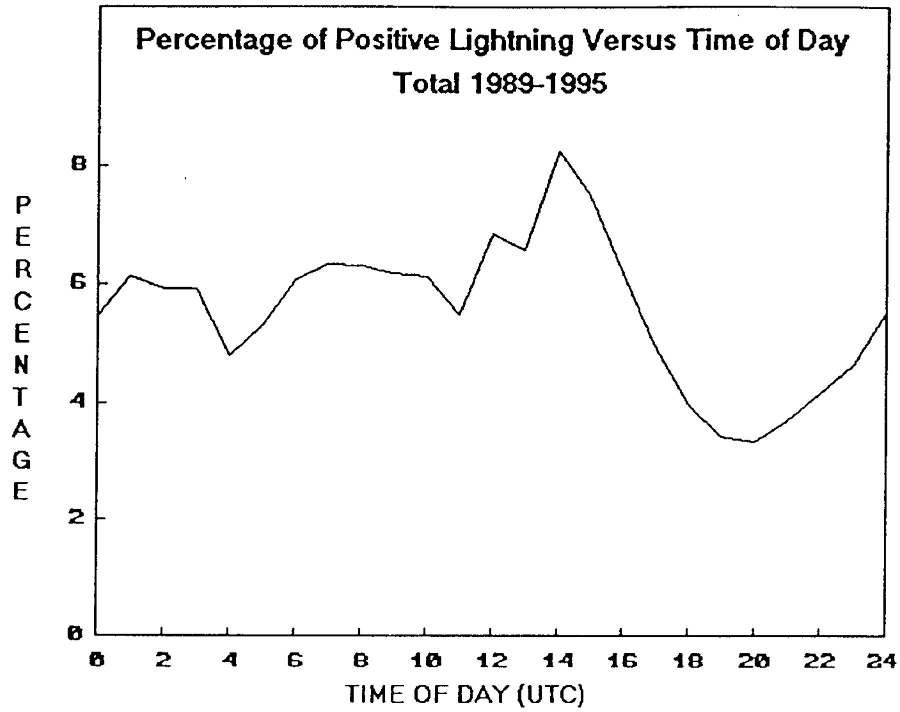

Figure 27. Percentage of positive lightning flashes versus time of day for the total period 1989 through 1995. Subtract 6 hours for Central Standard Time. Largest percentage found in the mid-morning local time.

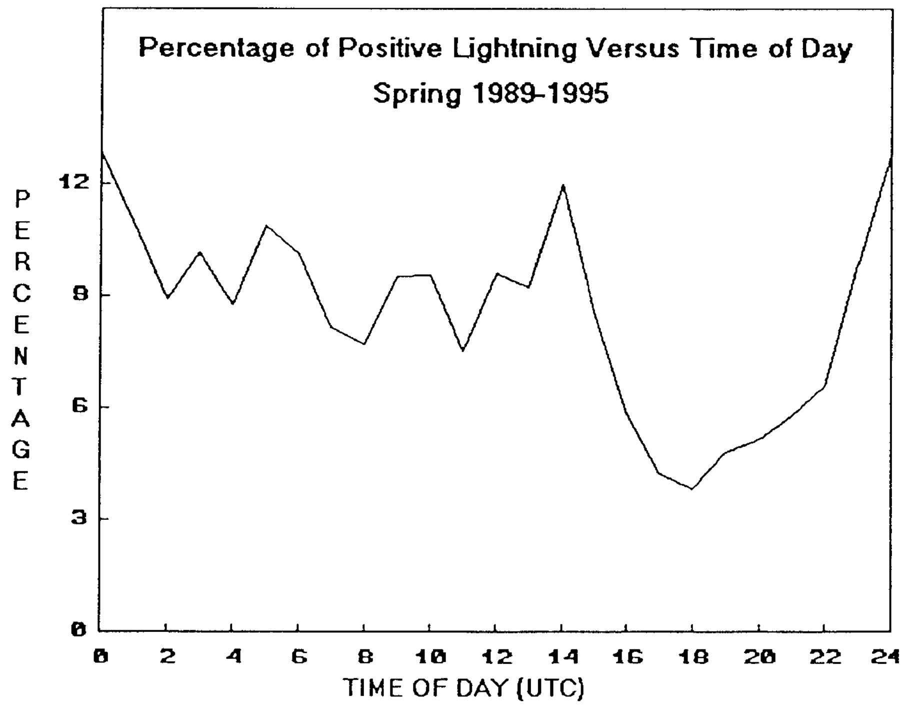

Figure 28. Same as Figure 27, except for the spring period (March-May) of 1989 through 1995. Largest percentages found in mid-morning and at 1800 CST.

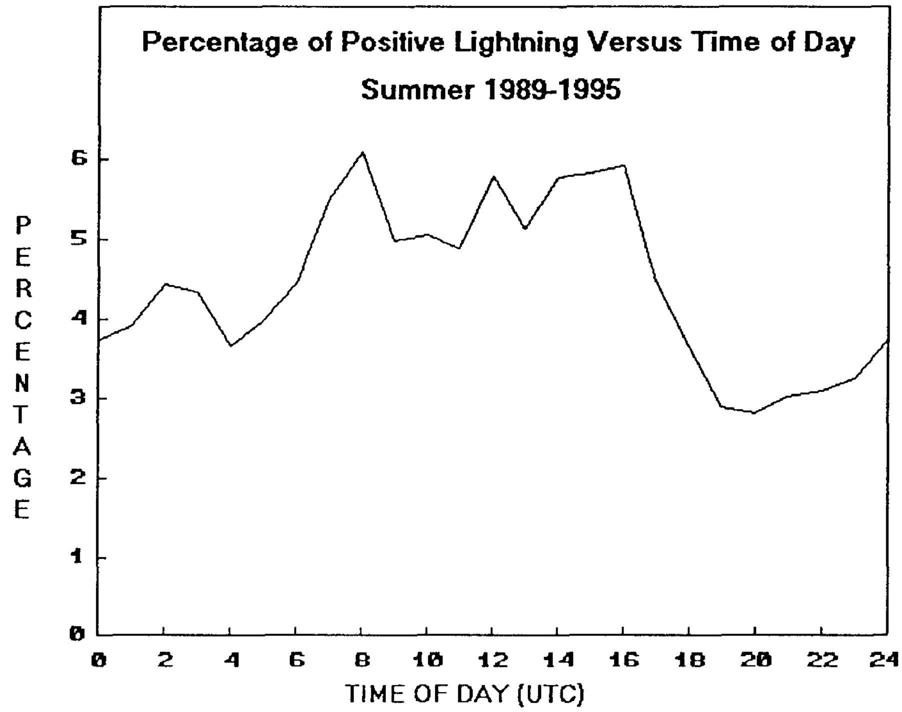

Figure 29. Percentage of positive lightning flashes versus time of day during the summer period (June-August) 1989 through 1995. Subtract 6 hours for Central Standard Time. Several maximums are observed at 0200 local and from early to mid-morning.

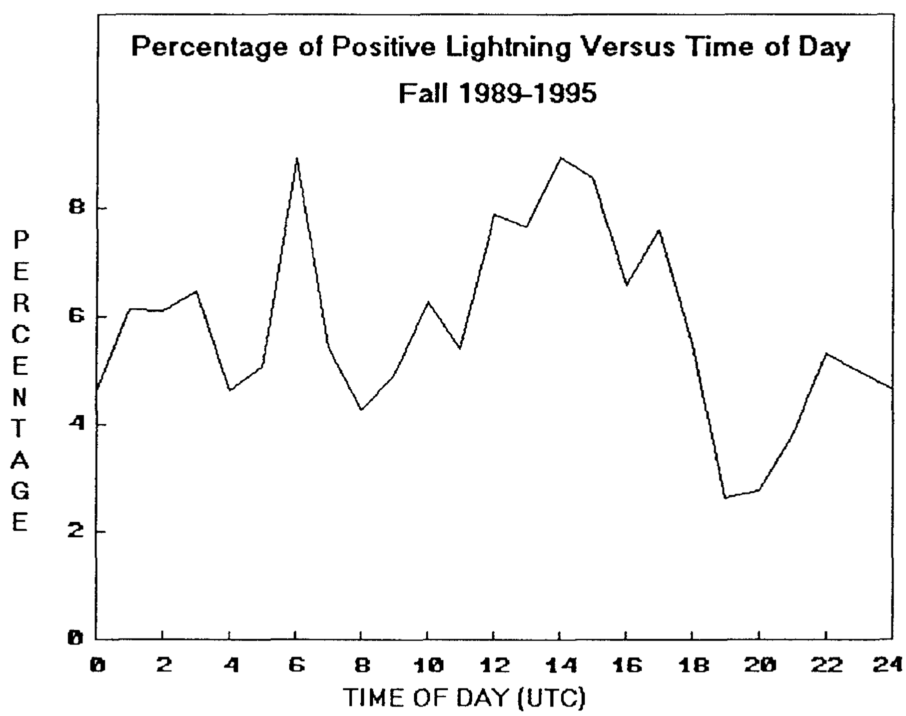

Figure 30. Same as Figure 29, except for the fall period (September-November) of 1989 through 1995. Maximums at midnight and mid-morning local time.

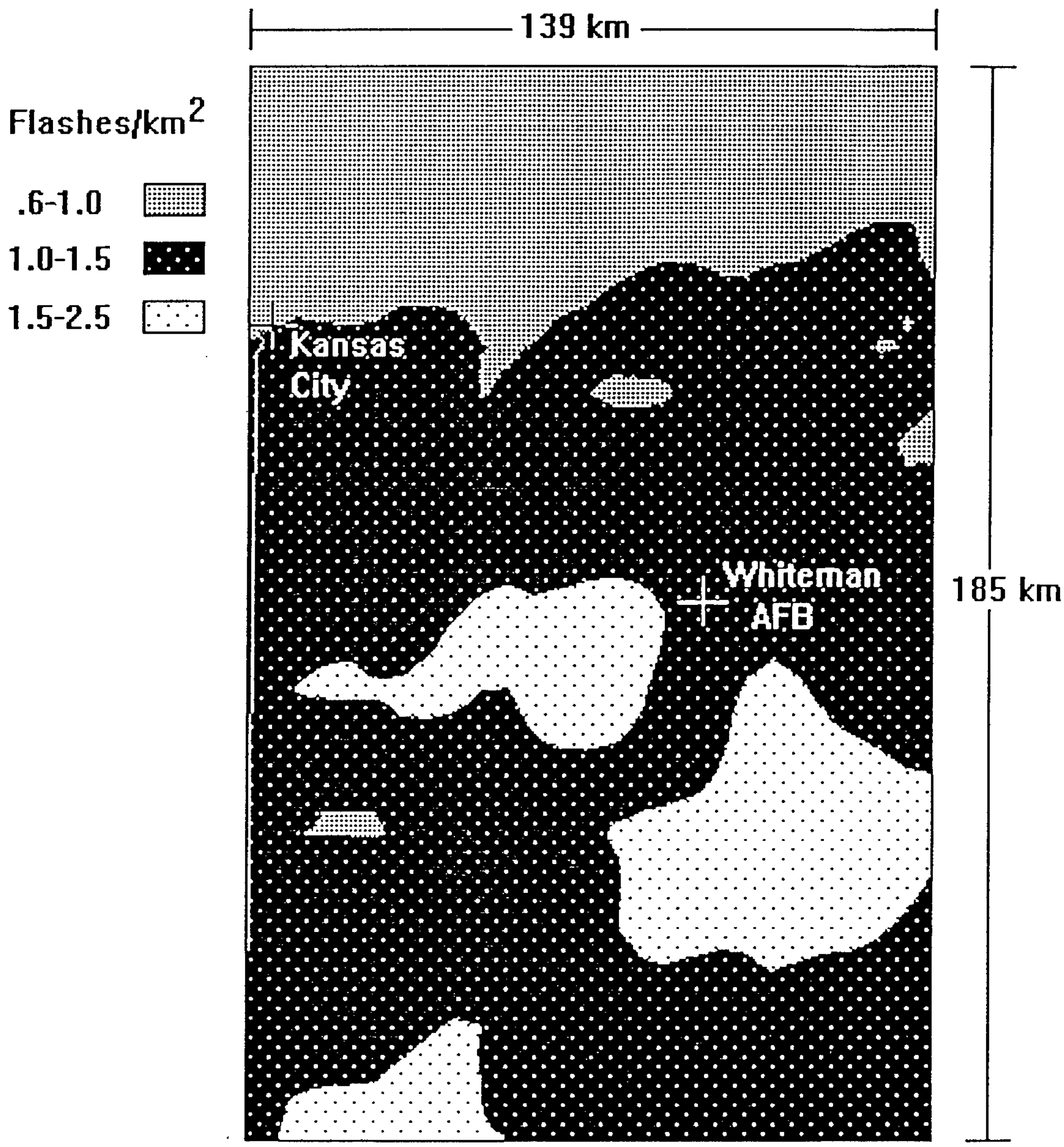

Figure 31. Average ground flash density per season during the spring period (March-May) 1989 through 1995.

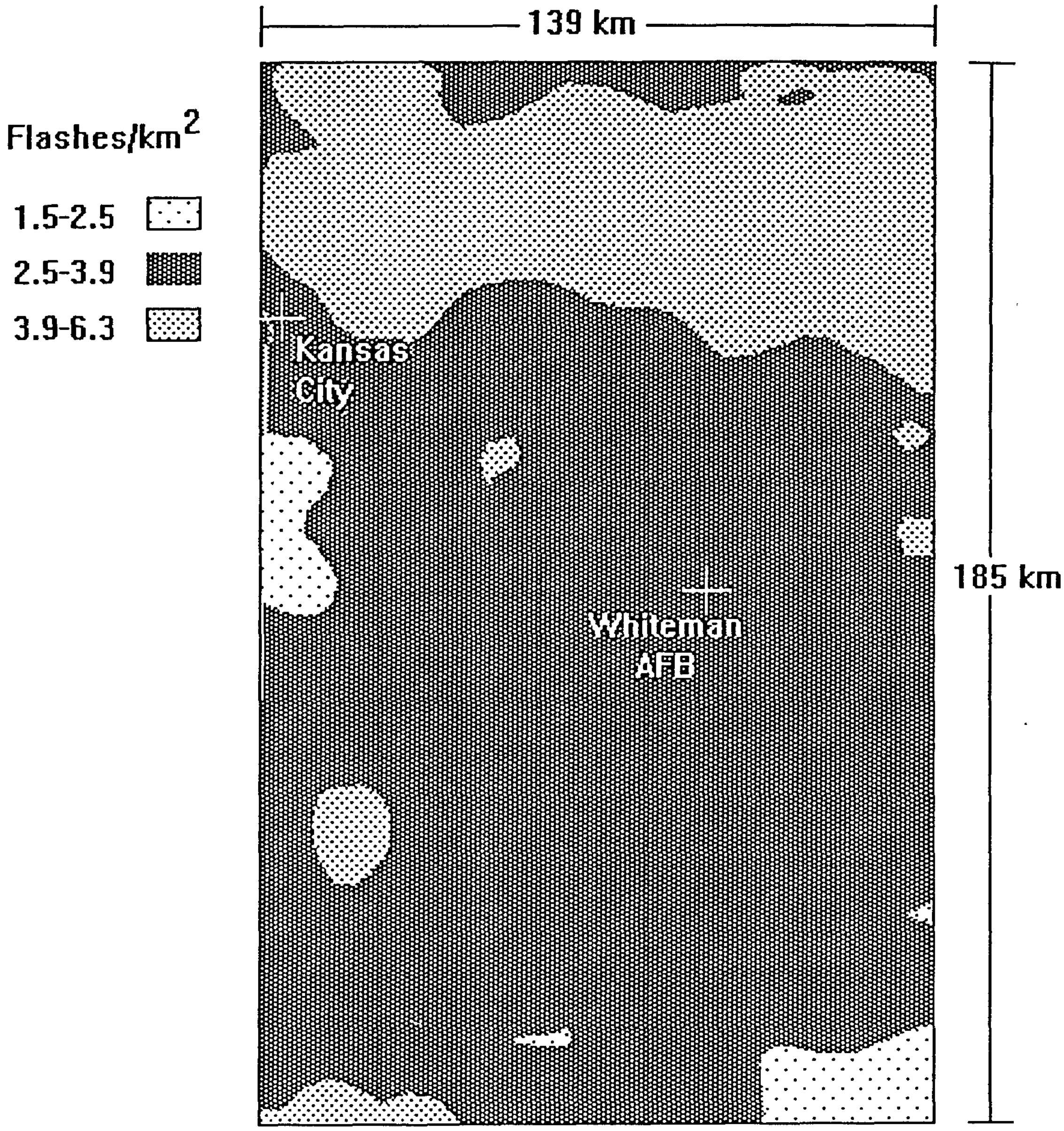

Figure 32. Average ground flash density per season during the summer period (June-August) from 1989 through 1995. Over 63% of all flashes were recorded during the summer season.

The northern one-third of the region averaged 3.9-6.3 flashes km^{-2}, while most of the remaining area averaged 2.5-3.9 flashes km^{-2}. Two areas of lower flash densities were evident, one at the southeast corner of the study area and another south of Kansas City. Both locations averaged 1.5-2.5 flashes km^{-2}.

The fall period had the lowest average GFD of the three studied seasons. Examination of Figure 33 shows that the highest flash densities were only 1.0-1.5 flashes km^{-2}, and were located in pockets mostly in the north and eastern sections of the box. A large minimum in GFD of less than 0.6 flashes km^{-2} was located in the southwest quarter of the region, with smaller areas near the southeast and northwest corners.

The yearly average GFD for the period 1989 through 1995 is shown in Figure 34. Not surprisingly, the total average resembled the summer season average. A maximum GFD value of 6.4-7.8 flashes km^{-2} was north of Whiteman AFB and just east-northeast of Kansas City. A smaller area of maximum value was near the southwest corner of the box. Several areas of minimum GFD values between 3.6-5.0 flashes km^{-2} were evident as well, with the largest areas near the southeast corner of the region and another just south of Kansas City.

The year-to-year GFD pattern showed a large variability. Figure 35 shows the GFD for 1993. Distinctly higher GFD contours were found in the northern third of the region as compared to the southern section with flash densities three to four times higher in some cases. A maximum of 19 flashes km^{-2} was observed approximately 70 km east-northeast of Kansas City. For comparison, Figure 36 contains the GFD for 1990, the year of the second highest flash total. Maximum GFD values were not only about half of those seen in 1993, but were found in the southern half of the study region. With the exception of 1993, an examination of each year of GFD contours showed that GFD values remained reasonably consistent from year-to-year, with typical values ranging from two to ten flashes km^{-2}. On the other hand, the locations of maximum and minimum GFDs showed large variability. While the topography of the area is uneven, with elevation generally ranging from 210-350 meters above sea level, terrain variations in the study area did not seem to influence spatial distributions of lightning frequencies. No preferred locations of maxima or minima were found in the yearly averages.

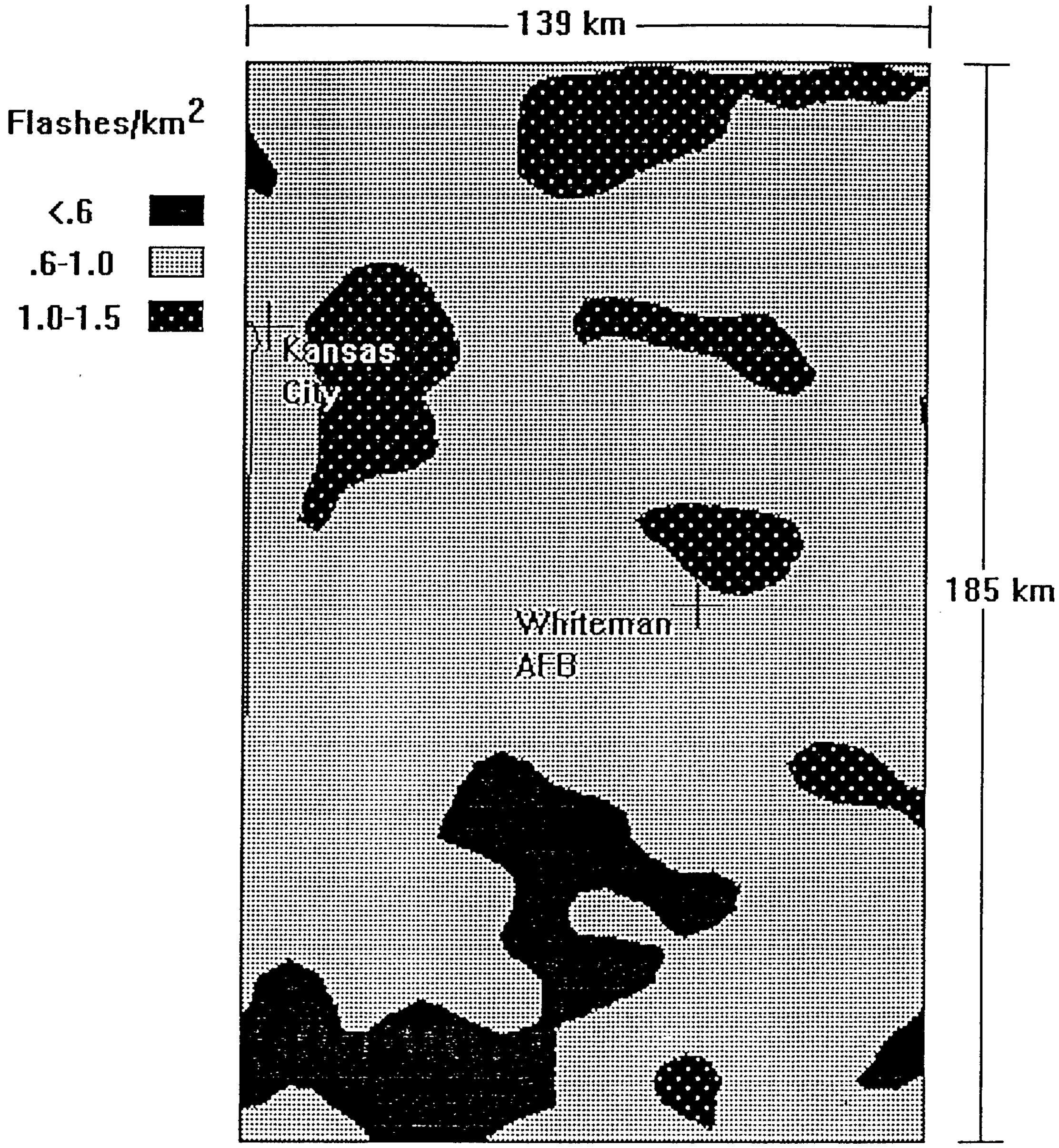

Figure 33. Average ground flash density per season during the fall period (September-November) from 1989 through 1995. The fewest flashes were detected during the fall as compared to spring and summer.

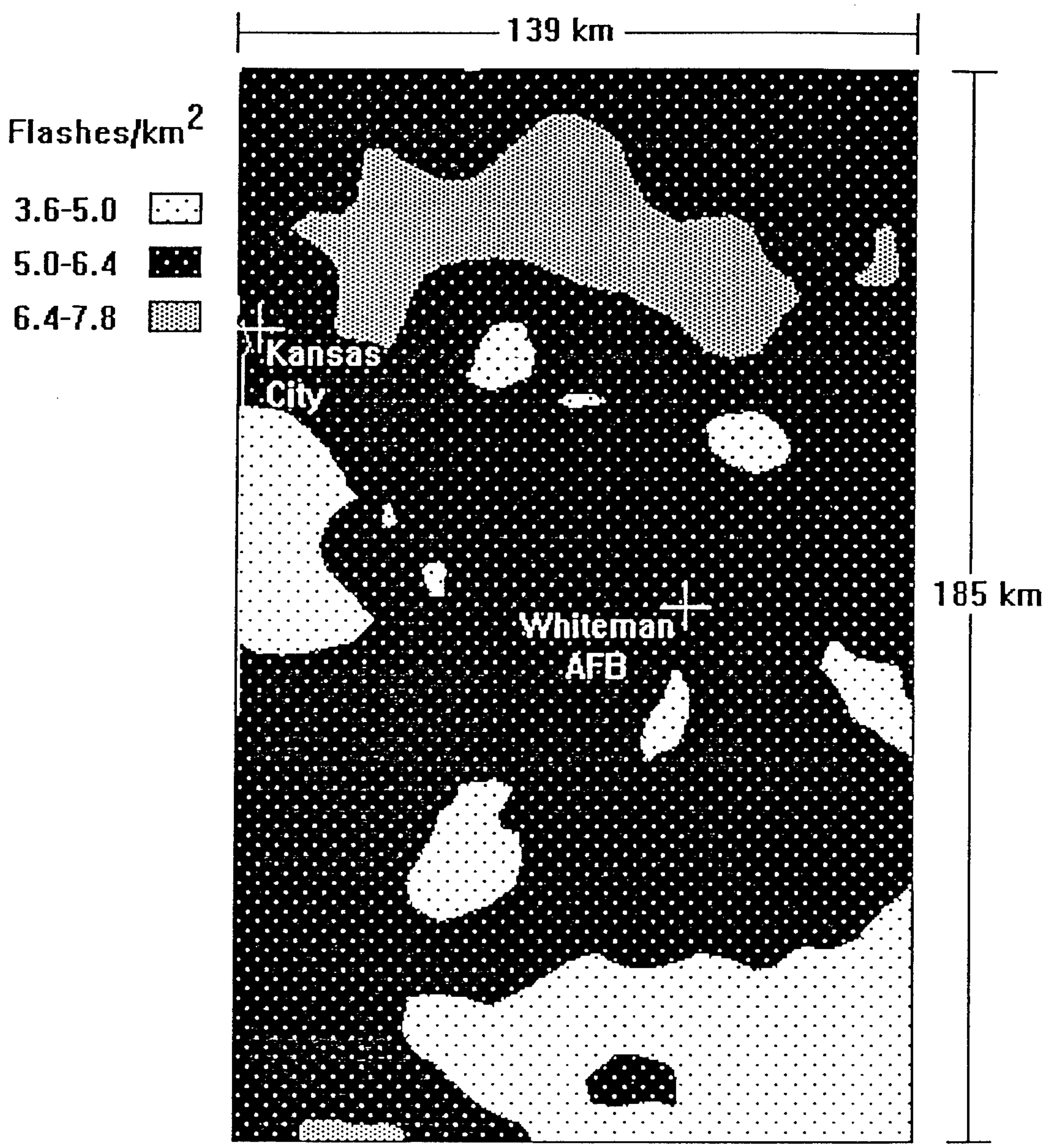

Figure 34. Average yearly ground flash density for the total period from 1989 through 1995.

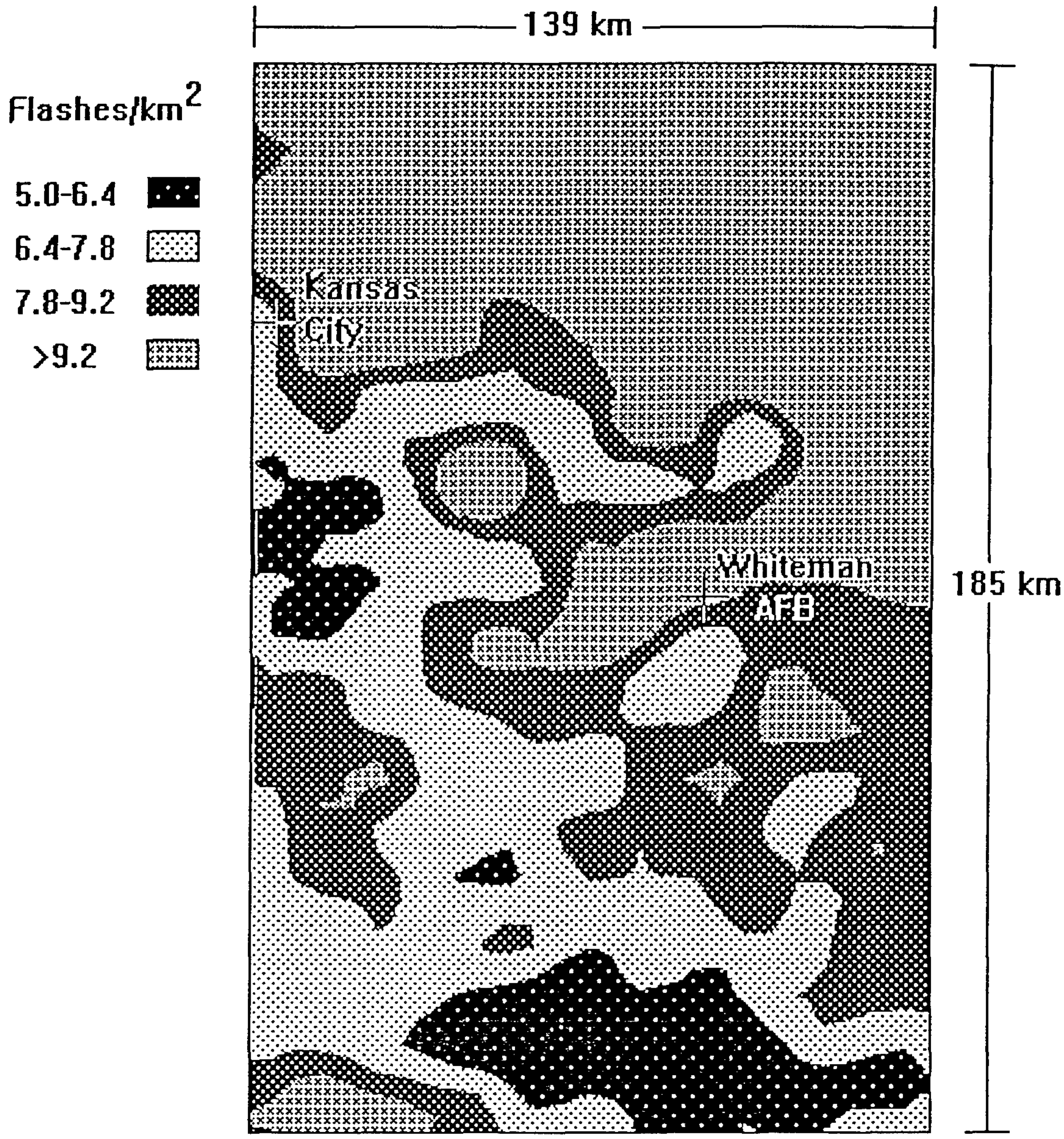

Figure 35. Ground flash density for 1993. Highest density value of 19 flashes km^{-2} is located approximately 70 kilometers east-northeast of Kansas City.

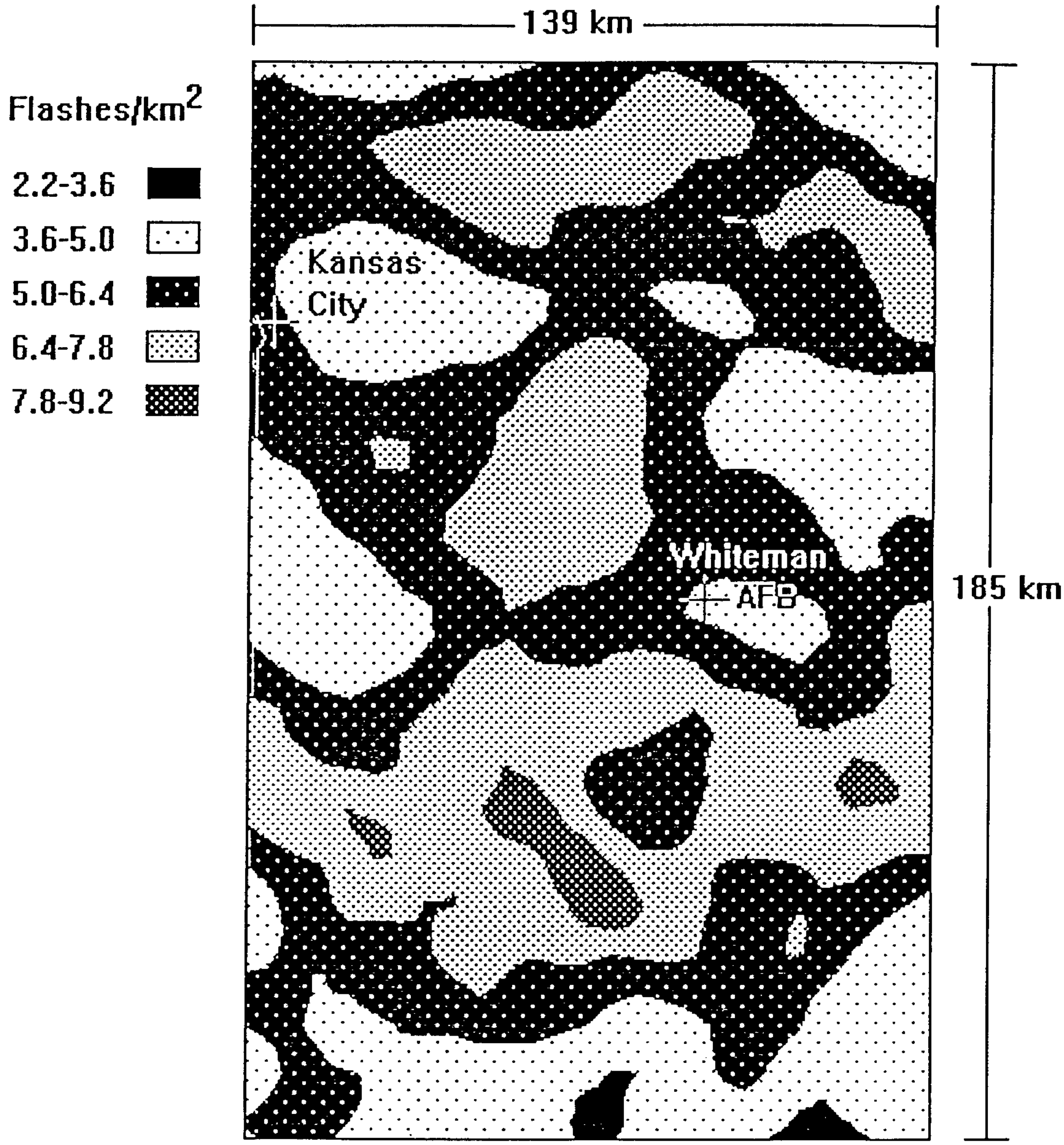

Figure 36. Ground flash density for 1990. Highest density value of 8.9 flashes km^{-2} is located approximately 50 kilometers south-southwest of Whiteman AFB. Maximum values were less than half of those observed in 1993, and found at the opposite end from where the maximum densities were located in 1993.

An analysis was performed to determine if the GFD averages or patterns were affected by either individual storm systems or yearly distributions of lightning flashes. All thunderstorm events for the spring period which produced at least 5000 measured flashes were compiled. A total of nine events were examined, which included one 6 day period in April 1992 in which three consecutive storm events produced over 8800 total flashes. These nine events alone produced over 43% of the total flashes measured for the spring period during the 7 year period. Figure 37 shows the total GFD for these nine events. A region of significantly higher GFD values was located to the south-southeast of Whiteman AFB, while the northern part of the box showed a distinct minimum in GFD.

Because 1993 had nearly twice as many flashes as any other year, several tests were conducted to determine what effects this year had on the GFD patterns. All lightning flashes from the summer of 1993 were deleted from the total for the summer period and the GFDs redone (Fig. 38). A comparison of Figures 32 and 38 shows that the overall pattern of GFD was much smoother for the non-1993 data set. A small GFD maximum was still located near the northern end of the region, but was significantly smaller than when the 1993 flashes are included. This clearly shows that the activity in 1993 influenced the GFD contours for the summer period. However, a minimum GFD contour was still located south of Kansas City. Interestingly, a minimum GFD area was located on the southeastern edge of the region, very close to where the maximum GFD contour was located for the spring period.

Finally, flashes for all of 1993 were removed from the total data set and flash densities redone (Fig. 39). Comparison of Figure 34 to Figure 39 shows that the GFD maximum in the northern section of the area is completely gone. Top values of 5.0-6.4 flashes km^{-2} were spread out in pockets over the map, with several larger areas evident. However, no patterns were recognizable. The average flash density over almost the entire box decreased by one to two flashes km^{-2}.

In contrast to Westcott's (1995) finding that CG lightning frequencies are greater within and downwind of most urban areas, no such effects were found in this study downwind of Kansas City. Although pockets of higher GFD values were observed in the average summer period GFD to the northeast of Kansas City, high variability from

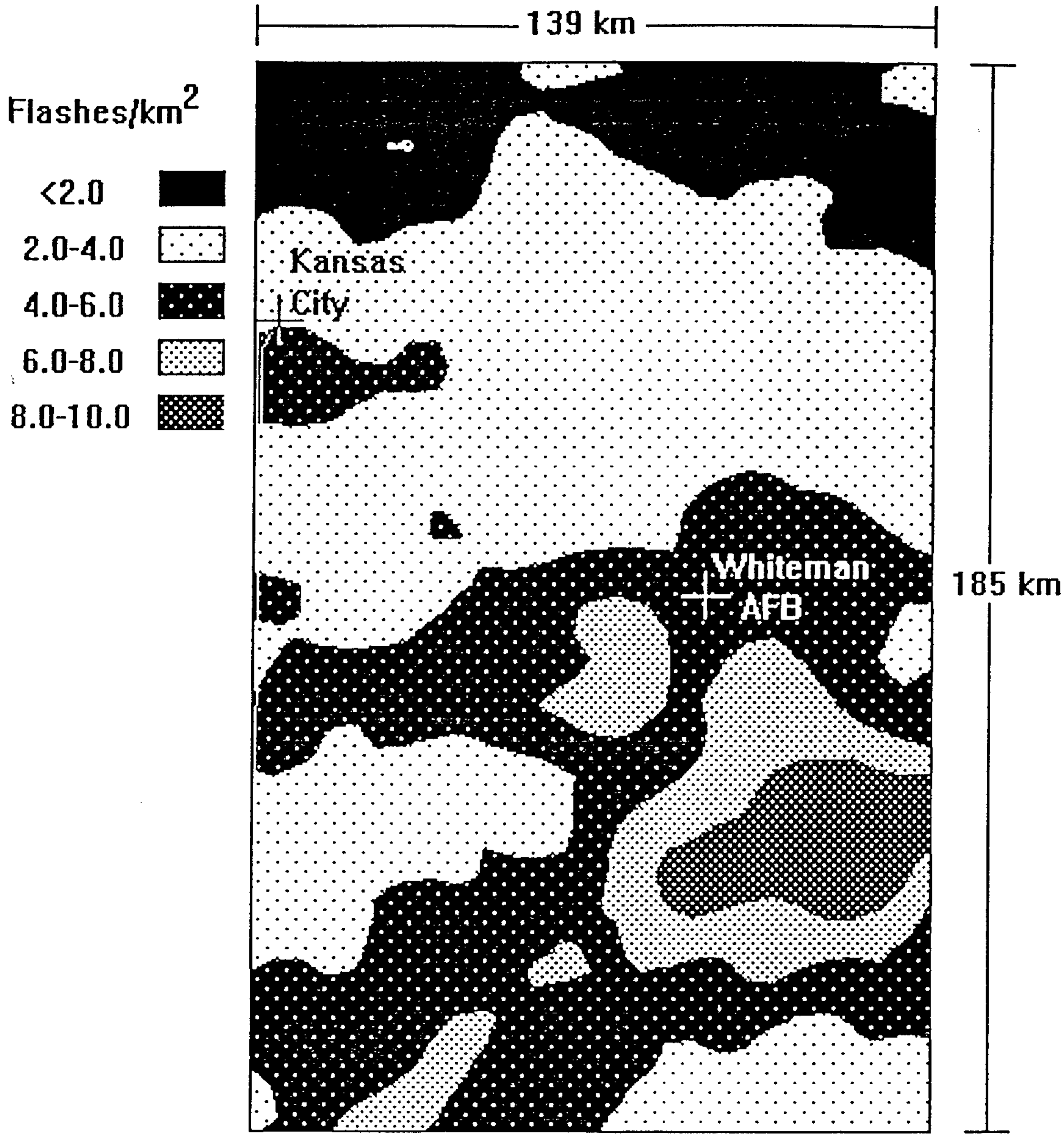

Figure 37. Ground flash density of the nine largest thunderstorm events from the spring period (March-May) of 1989 through 1995. Lightning flashes detected during these events totaled 68 514, over 43% of the total for the entire spring period.

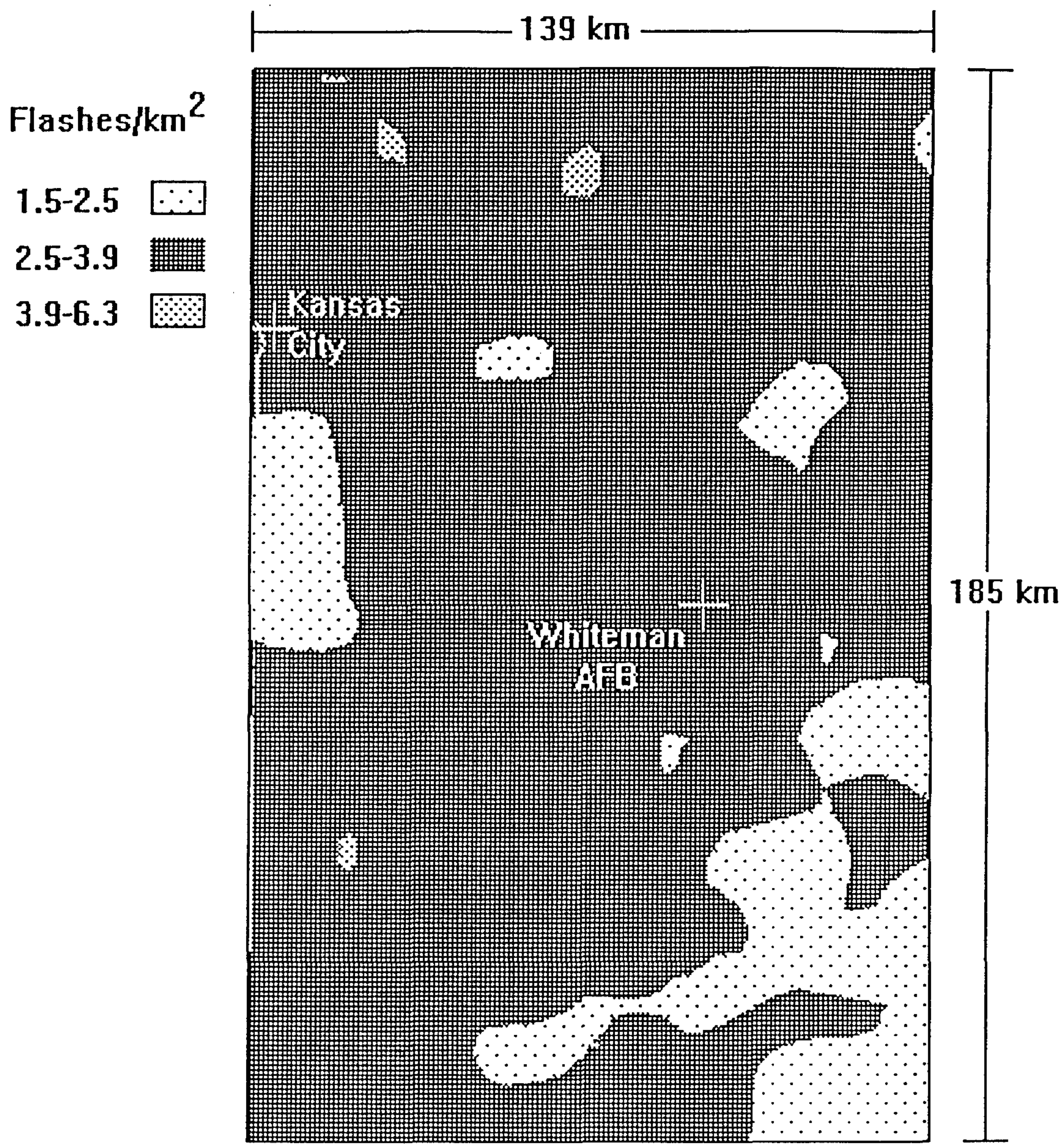

Figure 38. Average ground flash density for the summer period (June-August) from 1989 through 1995 without lightning flashes from Summer 1993 included.

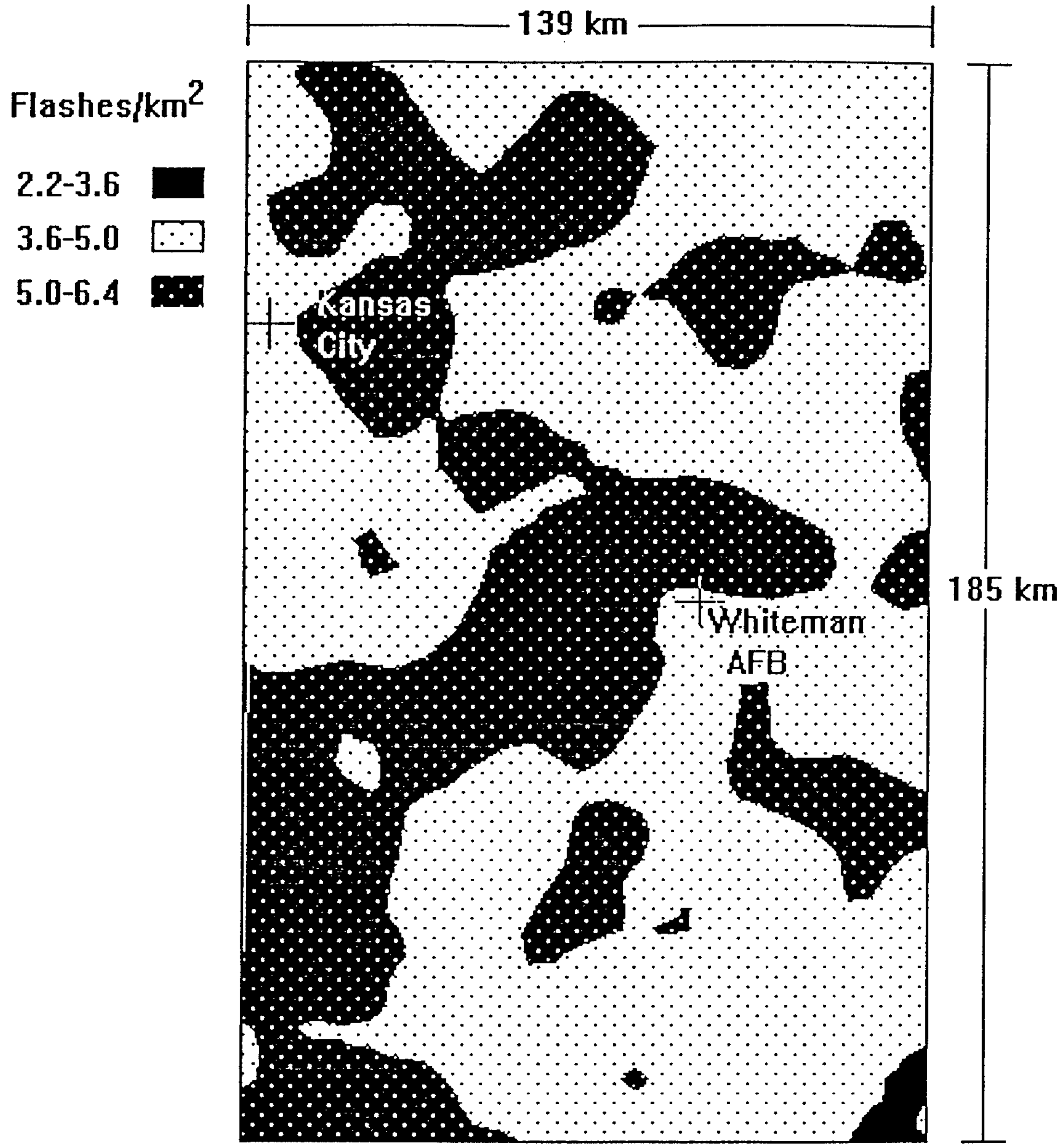

Figure 39. Average yearly ground flash density for the total period, 1989 through 1995 without lightning flashes from 1993 included. The average flash density decreased by one to two flashes km^{-2}.

summer to summer precluded seeing a consistent pattern that would suggest such an effect. However, this study was not conducted on the smaller spatial scale used by Westcott, nor was it done on an individual storm basis.

As expected, the ground flash density (GFD) values for positive flashes were much lower than for the total flashes recorded, and were easily influenced by individual storm systems that contained high amounts of positive lightning. Figure 40 shows the average positive GFD for the spring period from 1989 through 1995. A maximum in GFD values ran from the southeast corner towards the northeast, while pockets of lower GFD values were located in the northern half of the area. The area of maximum values was comparative to the region of values seen for total spring flashes (Fig. 31), once again suggesting that this area was a favored track for large springtime convective systems.

Little variation in ground flash density was seen during the summer and fall periods, and thus are not shown. Generally, summer GFD values ranged between 0.12-0.20 flashes km^{-2}, while fall values ranged mainly between 0.03-0.08 flashes km^{-2}. No distinguishable patterns were seen for either season. However, because the average GFD values were so low for the fall, they were highly susceptible to influence by individual storms.

The average positive GFD for the total period is shown in Figure 41. Comparisons of the positive GFD with the average GFD for all flashes (Fig 34) showed that while the maximum area of GFD values were located in the northern half of the study area, the maximum areas of positive GFD values were found in the southern half. This seems to be an apparent contradiction to the bipolar patterns found by Orville et al. (1988), Engholm et al. (1990), and Stolzenburg (1990). However, the region of study was isolated from a larger data set of lightning flashes. It is possible that for the maximum in GFD values for all flashes, a corresponding maximum GFD for positive flashes may be located to its northeast, but out of the study area. Similarly, it is possible that the maximum positive GFD values seen in Figure 41 correspond to a maximum total flash GFD region located to the southwest of the study area. Therefore, these results were inconclusive for locating bipolar lightning patterns.

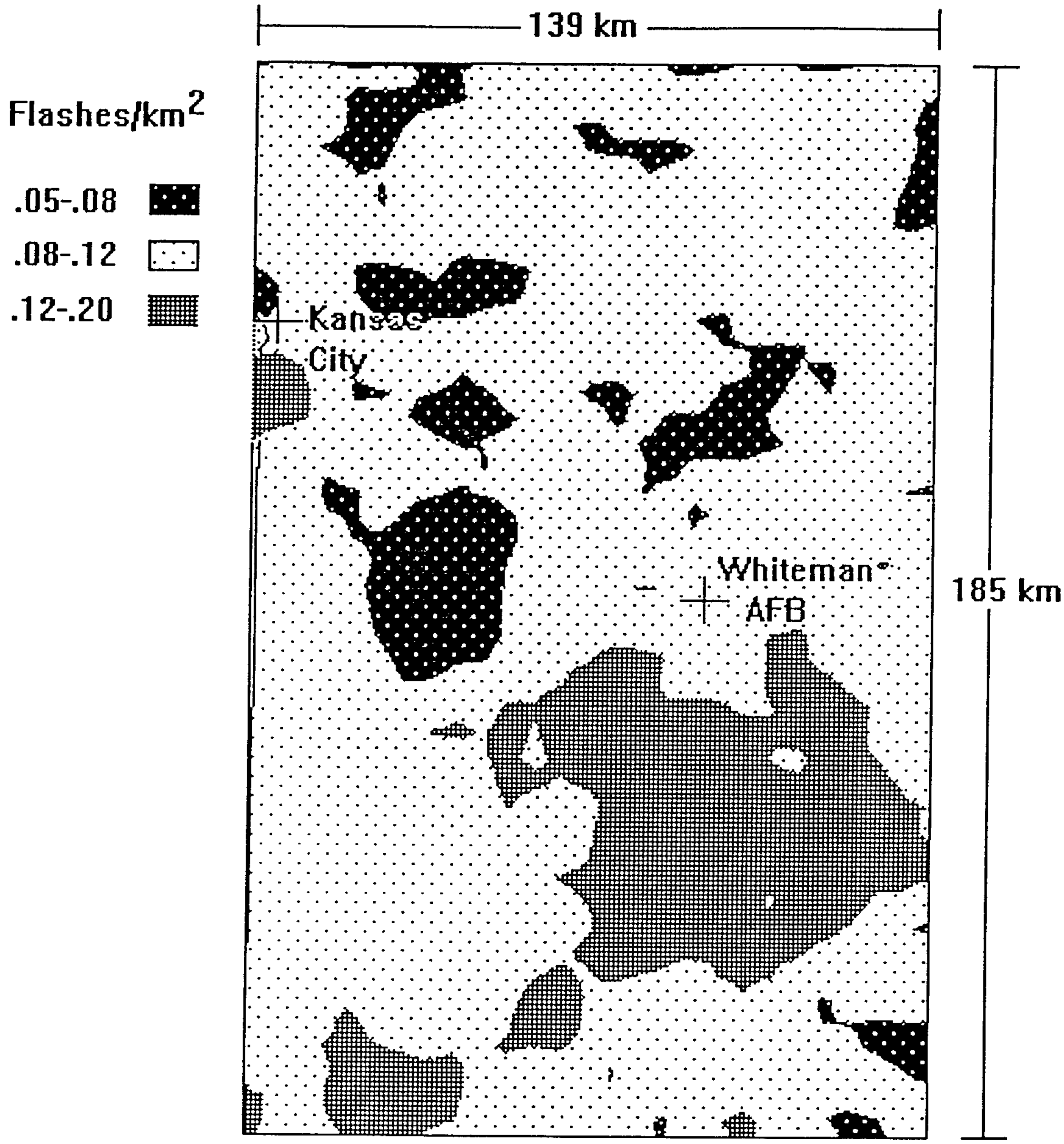

Figure 40. Average ground flash density of positive lightning flashes for the spring period (March-May) from 1989 through 1995.

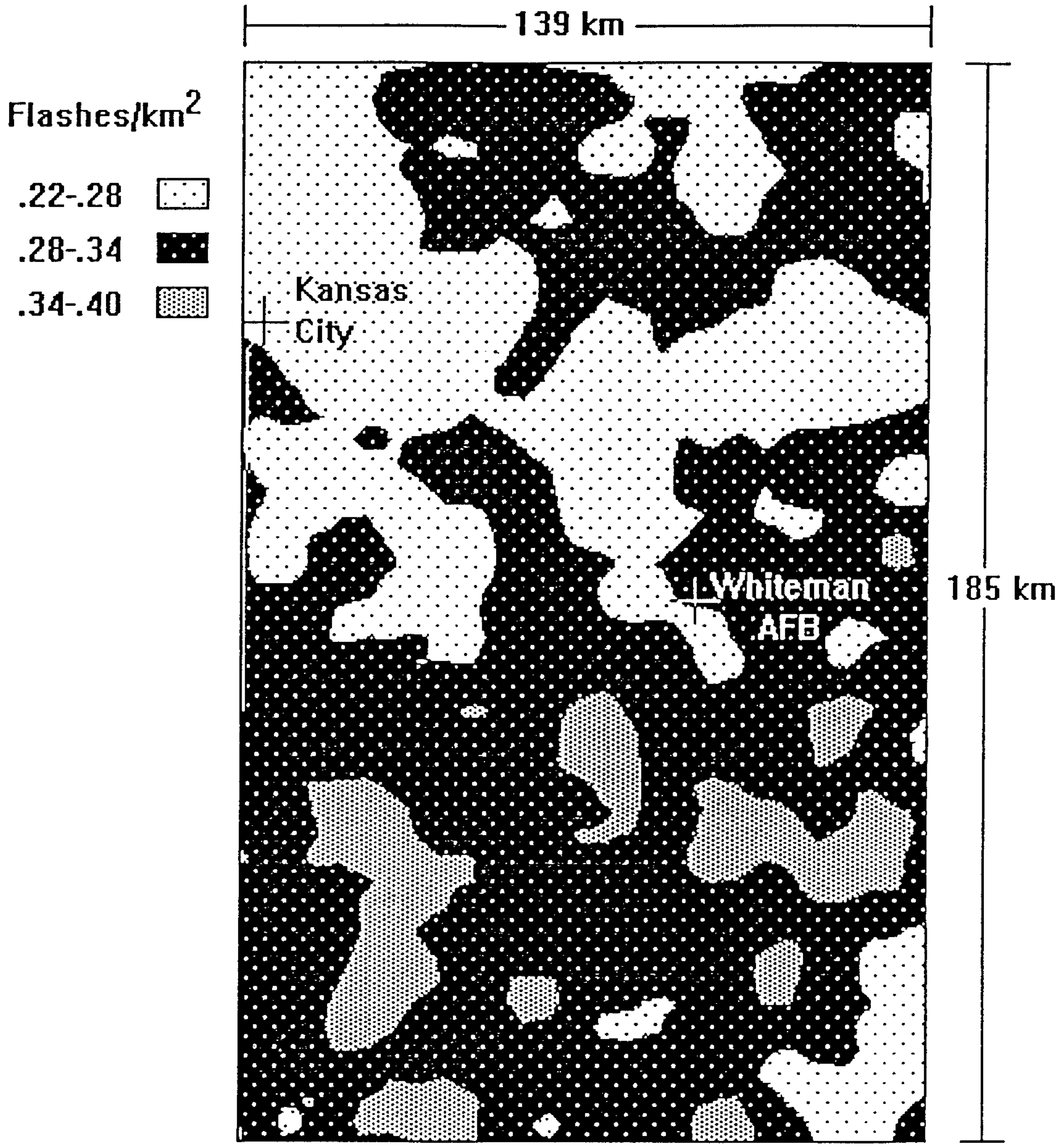

Figure 41. Average yearly ground flash density of positive lightning flashes for the total period 1989 through 1995.

c. First stroke peak currents

To measure first stroke mean peak current, all lightning flashes detected by the NLDN in the study area were divided into positive and negative polarity flashes. Both sets were then divided by month, season, and year for comparison.

Figure 42 is a graph of the monthly first stroke average peak current for negative flashes during the period 1989 through 1995. The winter months of December, January, and February all showed high mean peak currents. The rest of the year was very consistent with mean peak currents around 35 kA in March and April to a yearly minimum of 32 kA in June.

Figure 43 displays first stroke average peak currents for negative flashes during the spring season for each of the seven years. While some individual months showed slight variation, the average for each spring season during the first six years of the study only varied from 33 kA in 1991 to 39 kA in 1993. On the other hand, the lowest mean peak current for all three months was recorded in 1995. The mean for the spring of that year was 6 kA below the seasonal average for the entire period.

This trend continued into the summer season (Fig. 44). The lowest mean peak currents for both June and July were measured in 1995, with monthly averages 6 kA and 8 kA lower than normal, respectively. August 1995 was also below normal, and only the 1991 mean was lower. For the entire season, the mean peak current for the summer of 1995 was about 26 kA, 7 kA below the 7 year average.

One interesting phenomenon was the consistently higher than normal mean peak currents for the summer of 1993. This trend actually began in May and lasted through the end of the year. Not only were nearly twice as many lightning flashes recorded during these months of 1993 than in any other year, but the mean peak current was continually about 4 kA higher per month than the average for those months. While this may be related to the excessive amount of precipitation measured in the area during that year, further study is needed to explain this occurrence.

Monthly peak currents for the fall season are seen in Figure 45. As previously mentioned, 1993 had higher than normal peak currents for each month. Notice also that although the average peak current in September of 1995 was lower than any other year,

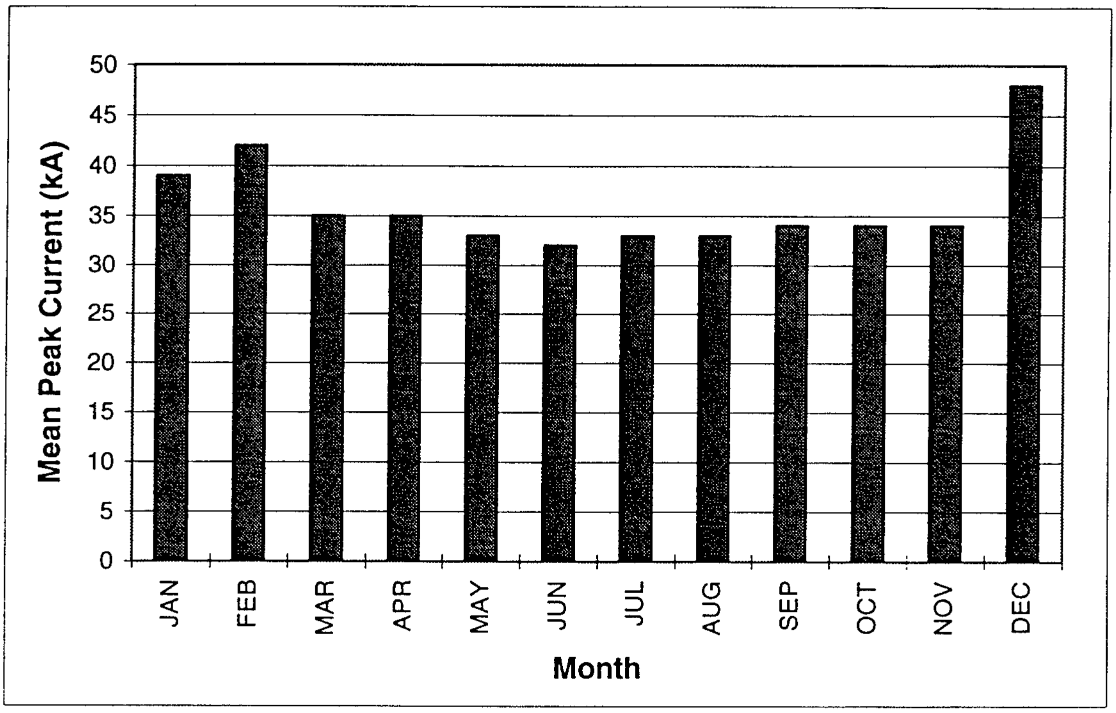

Figure 42. Monthly mean peak current (in kA) for negative flashes during the period 1989 through 1995.

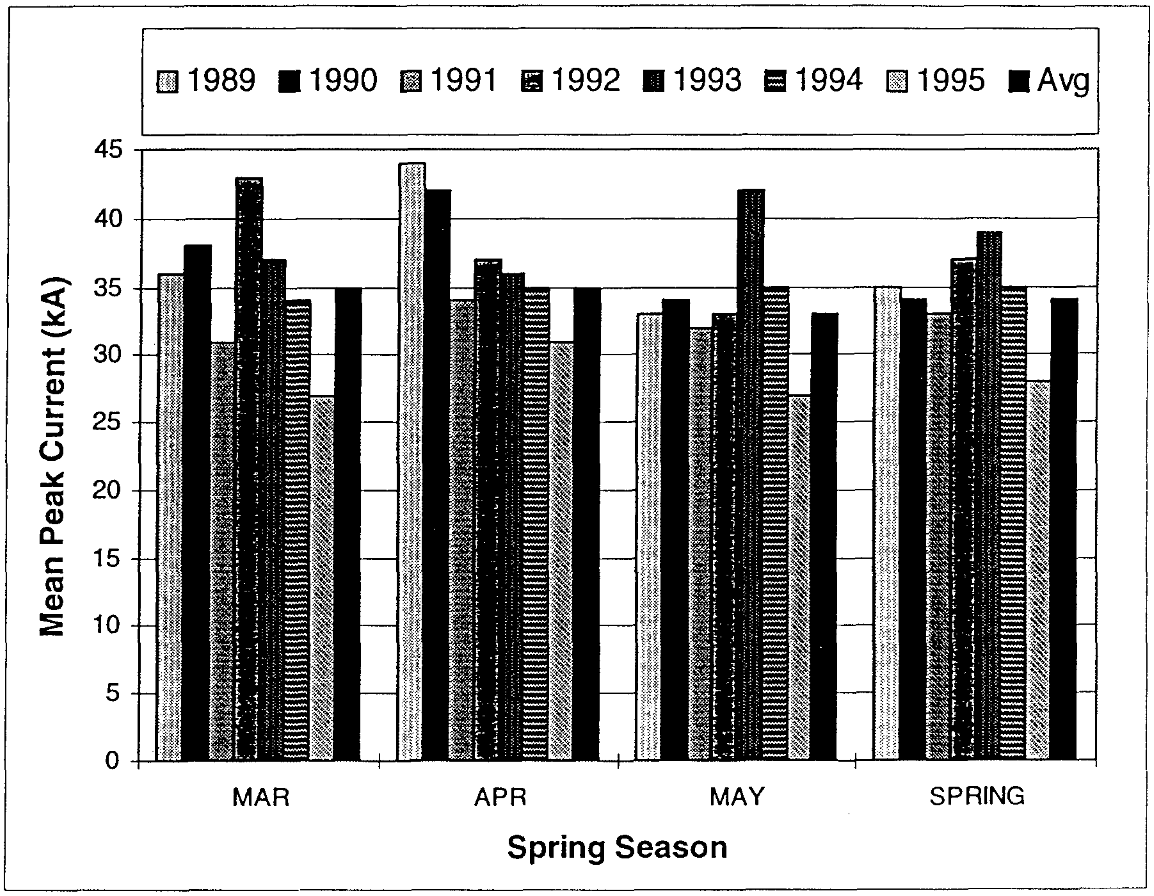

Figure 43. First stroke mean peak current for negative flashes during the spring season (March-May) from 1989 through 1995, and the overall average for each month. Seasonal average is included as well. The means for 1995 are well below the average for each month.

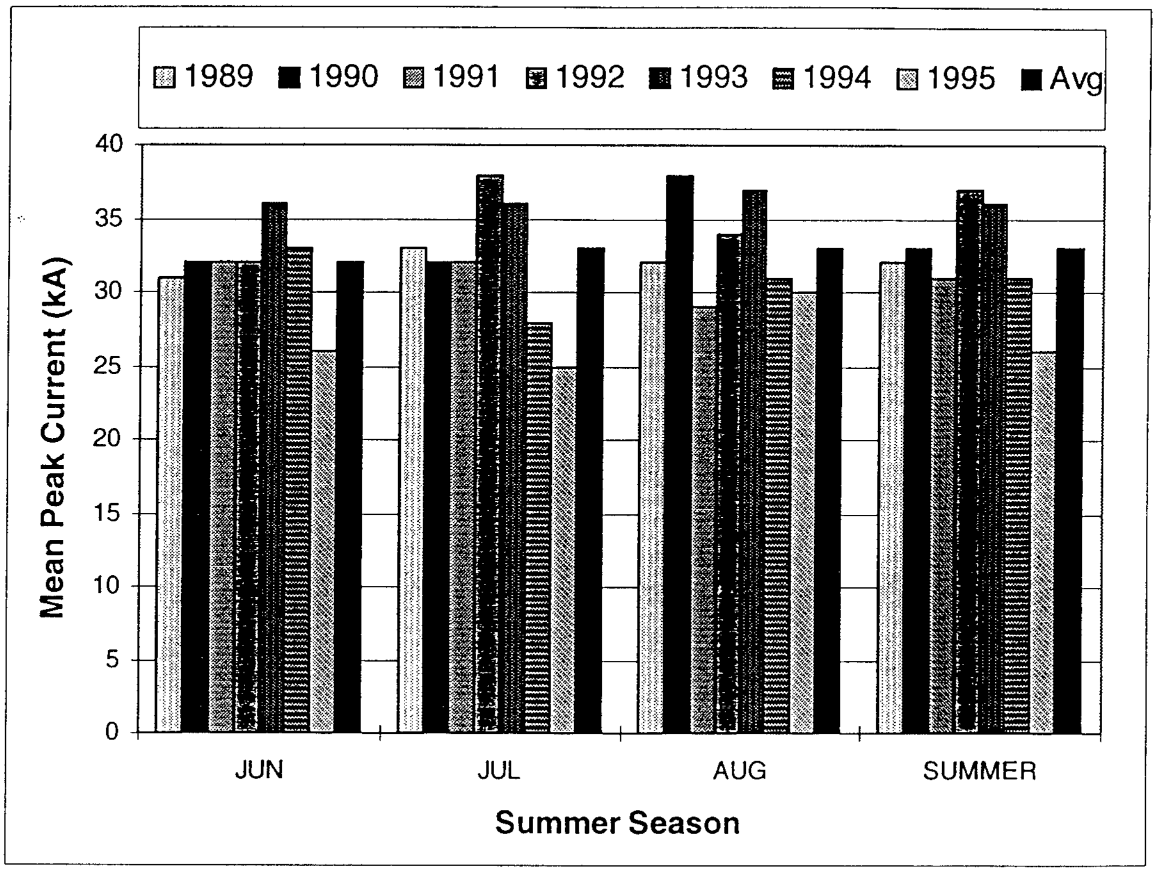

Figure 44. First stroke mean peak current for negative flashes during the summer season (June-August) from 1989 through 1995, and the overall average for each month. Seasonal average is included as well. Mean peak currents for 1995 remained well below the monthly averages.

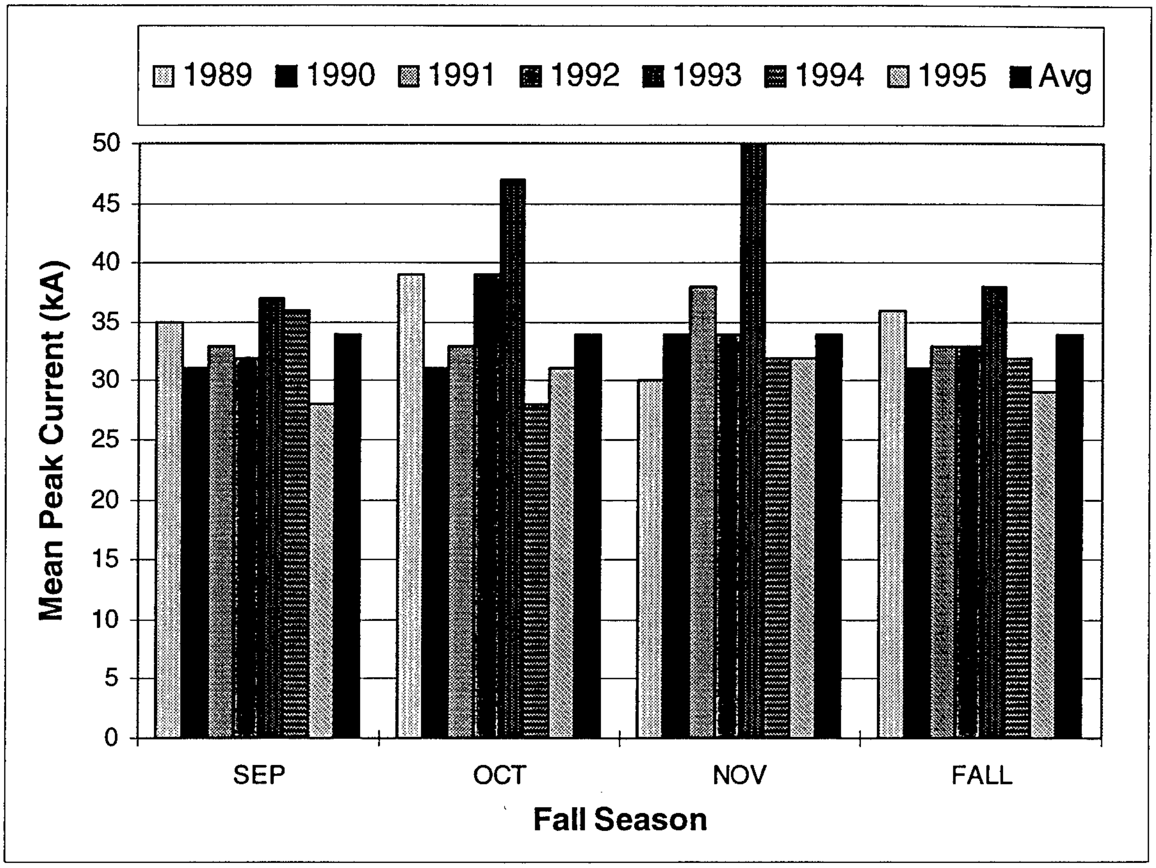

Figure 45. First stroke mean peak current for negative flashes during the fall season (September-November) from 1989 through 1995, and the overall average for each month. Seasonal average is included as well.

this trend did not continue into the cooler months of October and November.

Cummins et al. (1995) claim that the integration of the TOA system into the NLDN improved detection of lightning flashes with lower peak currents. To test this claim, all negative flashes were compared against designated increments of peak currents to determine how many lower peak current flashes were recorded on a yearly basis. Results are shown in Table 7. The first column is the number of flashes with peak currents below 12 kA that were measured in the study area during each year. Numbers ranged from 309 in 1992 to 1908 in 1995. The total for 1995 was nearly 500 more flashes than for the next closest year, 1994. It must be remembered that the TOA system was integrated into the NLDN in 1994, so the increase for that year may not be surprising. Between 12-16 kA, the numbers ranged from 2038 in 1992 to 11 454 in 1995. Once again, 1994 and 1995 had far more flashes than any other year. The trend continued for flashes between 16-20 kA, with the 1995 total nearly double the total of most years except 1993 and 1994. For flashes between 20-24 kA, the gap almost disappeared, and 1995 actually had fewer flashes than 1993. Finally, for negative flashes with peak currents above 24 kA, 1995 had the fewest flashes. Also note that 1993 had twice as many flashes above 30 kA than any other year.

A comparison was made between 1995 and a year with a similar number of negative flashes, 1991. During 1995, 88 017 negative flashes were recorded, as opposed to 85 025 in 1991. The number of flashes in each increment for 1995 were compared to those in 1991 by ratio (Fig. 46). The graph shows more than twice as many flashes were detected below 12 kA in 1995 than in 1991. For flashes between 12-16 kA, the ratio was 2.66 to one. However, between 20-24 kA, the ratio was only 1.20 to one. Finally, 34% fewer flashes were detected between 24-30 kA in 1995 than in 1991.

The cumulative percentage of negative flashes above first stroke peak current values are given in Figure 47. The graph is the percentage of all negative flashes that were above a selected peak current value. The dashed line is for all negative flashes recorded from 1989 through 1993. The solid line represents all negative flashes recorded in 1994 and 1995. For example, about 85% of all flashes recorded from 1989 through 1993 were above 20 kA. For the period 1994 through 1995, only about 65% of all negative flashes

Table 7. The number of negative polarity cloud-to-ground lightning flashes during 1989 through 1995 that had first stroke peak currents (in kA) between designated threshold increments.

	PEAK CURRENT DESIGNATED INCREMENT					
YEAR	<12 kA	12<=x<16 kA	16<=x<20 kA	20<=x<24 kA	24<=x<30 kA	>=30 kA
1989	667	3484	7940	10798	15924	33629
1990	1193	4745	10744	15265	22183	47950
1991	897	4300	9879	13405	19373	37171
1992	309	2038	6040	9716	15726	38782
1993	529	3253	11942	21889	35860	94077
1994	1434	6330	11999	14057	17885	37706
1995	1908	11454	19292	16129	14766	24468
TOTAL	6937	35604	77836	101259	141717	313783

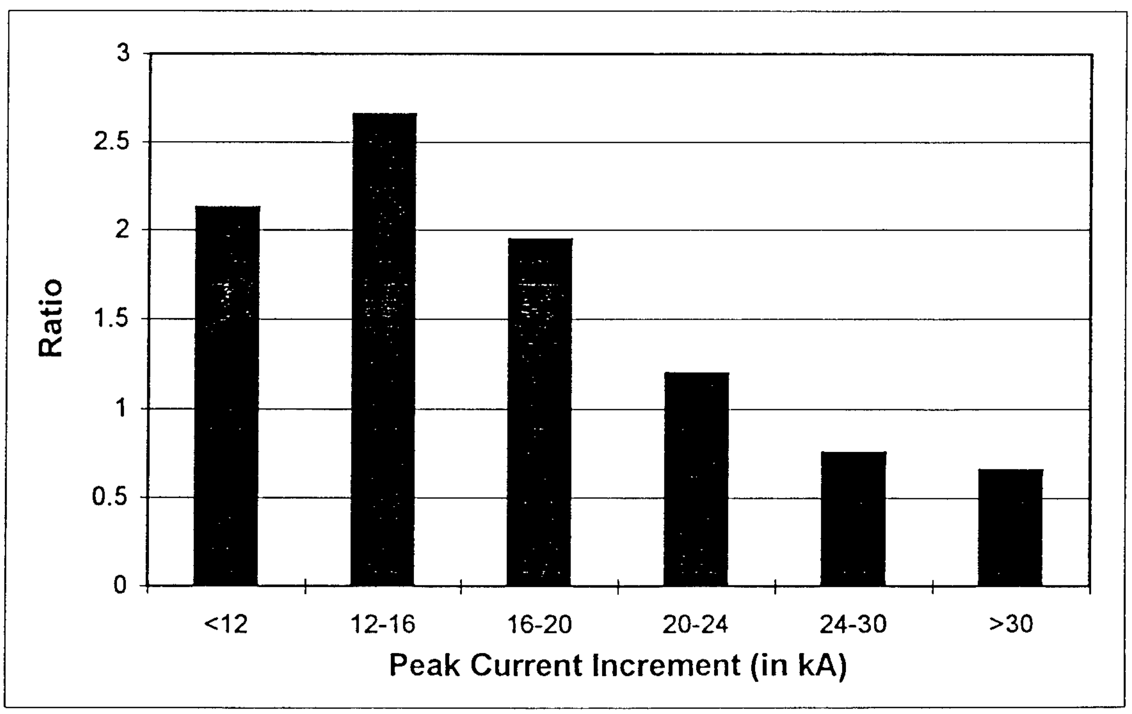

Figure 46. Ratio of negative flashes in 1995 against flashes in 1991 that occurred in each peak current increment. Over twice as many flashes below 20 kA were observed in 1995 compared to 1991. A decrease in the number of flashes was observed above 24 kA.

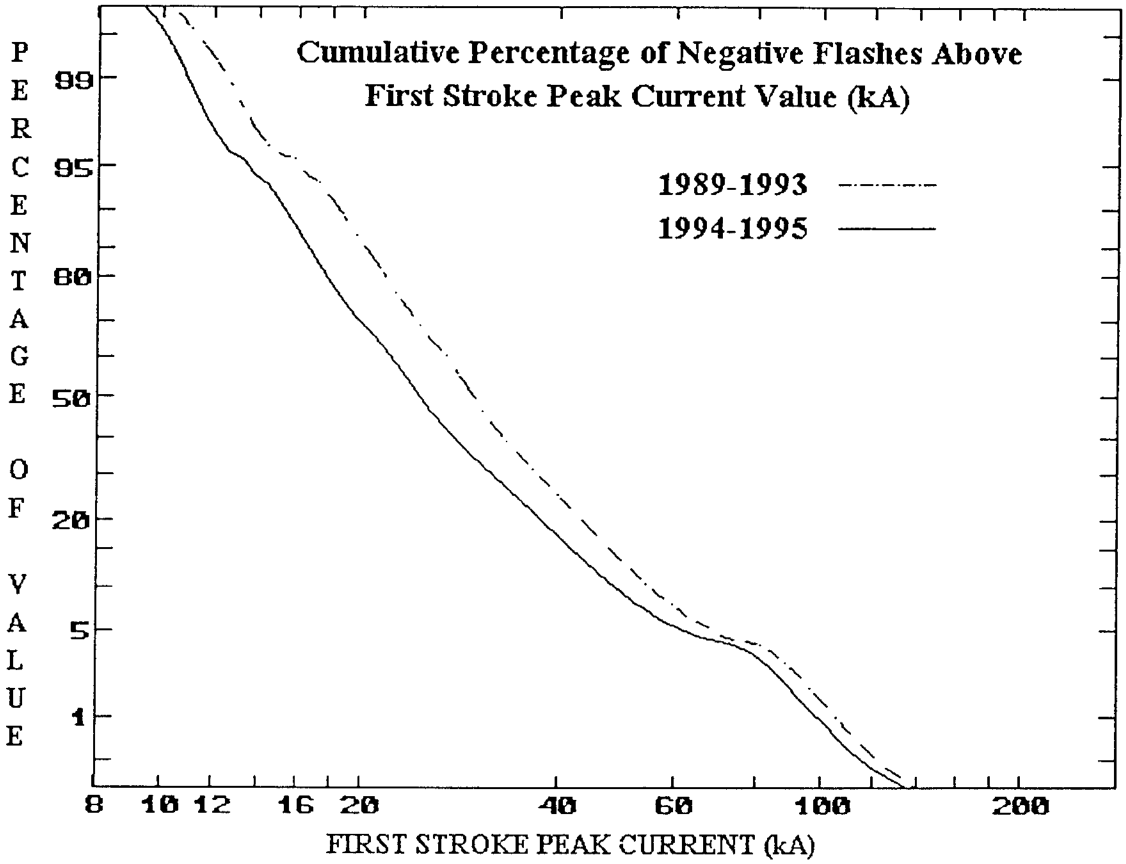

Figure 47. Cumulative percentage of all negative cloud-to-ground lightning flashes above first stroke peak current values (kA) for two data sets: 1989 through 1993, and 1994 through 1995.

had peak currents greater than 20 kA. The solid line is consistently below the dashed line, which shows that a higher percentage of lower peak current flashes were being detected during the last two years.

Analysis on first stroke average peak currents for positive lightning was performed in the same manner. Figure 48 shows the monthly mean peak current for the seven year period. Maximum peak currents were found in the winter, with an 85 kA mean for December. Peak currents generally declined until late spring, then remained nearly steady throughout the summer, with a minimum value of 36 kA in August. Peak currents increased again during the fall.

Positive flash mean peak currents were examined on a monthly and seasonal basis. Figure 49 displays the average peak currents for positive flashes during the spring season. Two particular years stand out. 1989 had a consistently high peak current, with an average for the spring about 18 kA higher than the norm. This may have been because the NLDN was new and adjustments were still being made. It is highly likely that the system was simply measuring flashes with very high peak currents and missing many positive flashes with lower currents. On the other hand, 1995 had a continually lower mean peak current, with a spring mean 14 kA below the average for the seven years. Once again, this trend continued through the summer (Fig. 50), although 1991 mean peak currents were actually lower than those for 1995. Meanwhile, peak currents for 1992 were much higher than normal. The percentage of positive lightning was about average during that summer (refer to Figure 8), but a series of storms that affected the area regularly had positive lightning flashes with high peak currents. One storm in particular produced its own fireworks on 4 and 5 July 1992. Four-hundred sixteen flashes were of positive polarity, 23% of the total. The mean peak current was 73 kA, with 79 positive flashes having peak currents over 100 kA.

For the fall season (Fig. 51), September and November were uniform in average. No positive flashes were recorded in November of 1989. The exceptionally high mean peak current of 108 kA for October of 1995 is worth mentioning. A single thunderstorm complex moving over the region between 0700-1700 UTC on 10 October was responsible for this anomaly. Of the 1695 flashes recorded for this storm, only 138 (8.1%) were of

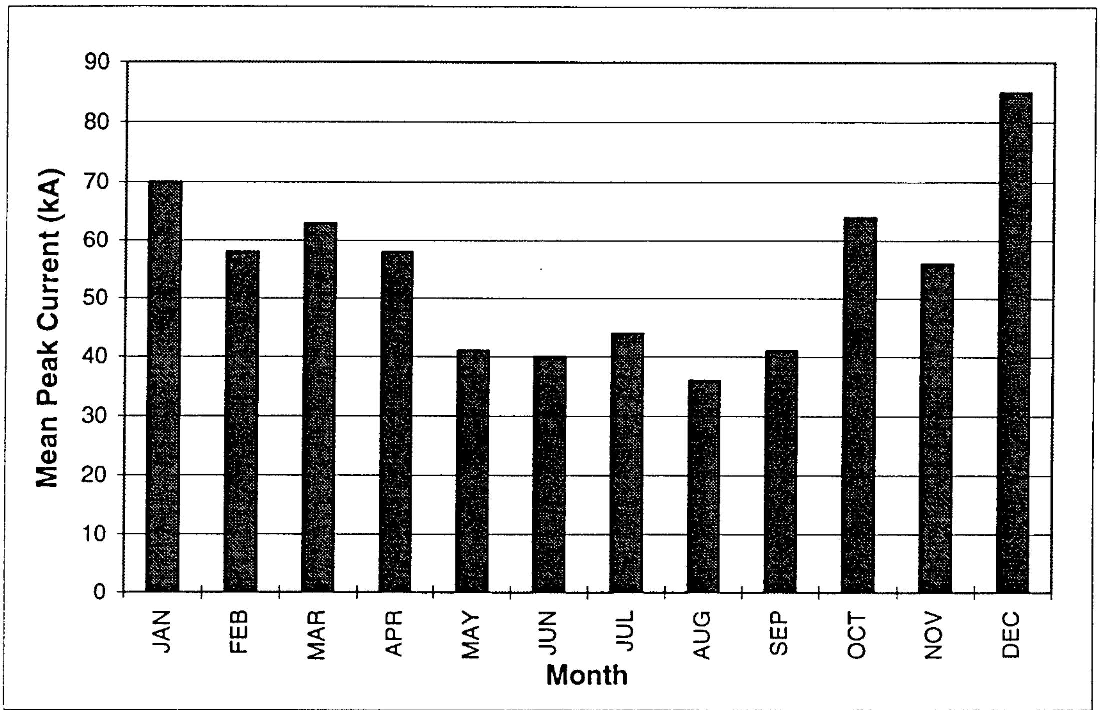

Figure 48. Monthly mean peak current (in kA) for positive flashes during the period 1989 through 1995.

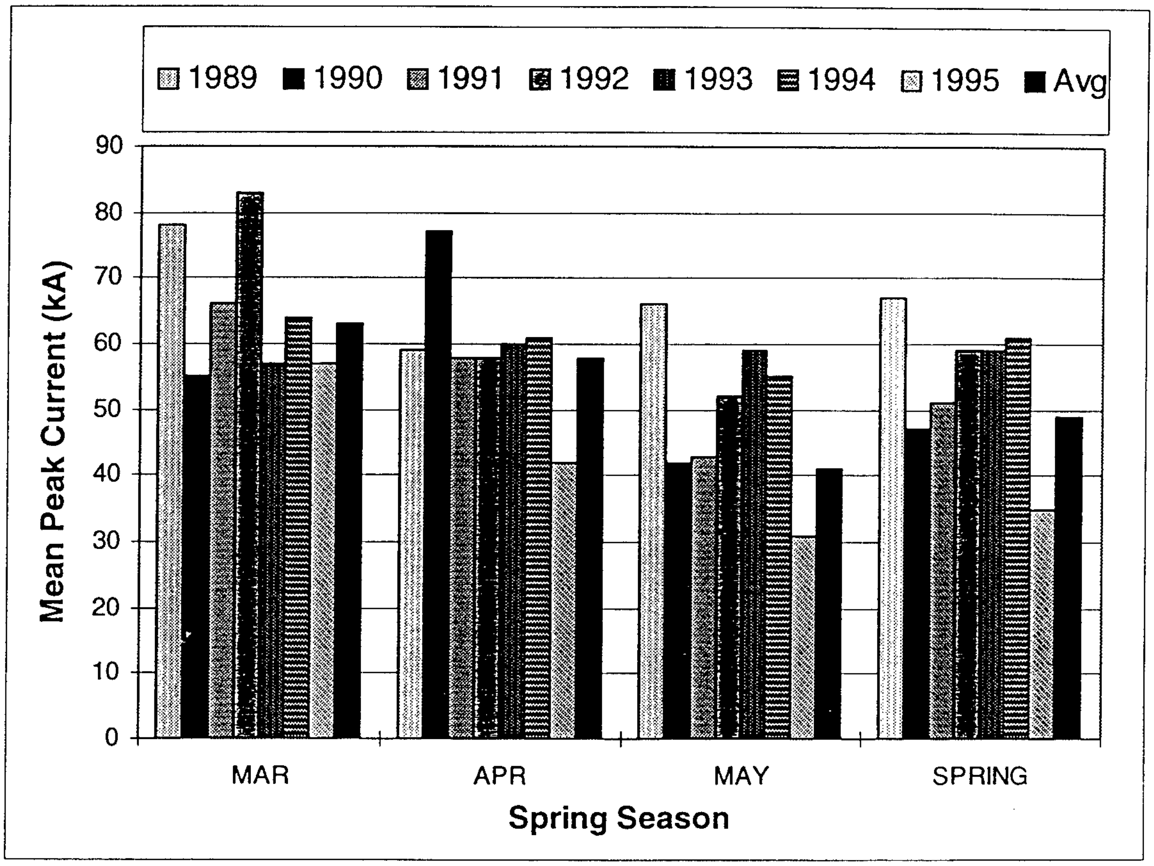

Figure 49. First stroke mean peak current for positive flashes during the spring season (March-May) from 1989 through 1995, and the overall average for each month. Seasonal average is included as well. Peak currents for 1995 are well below the monthly and seasonal averages.

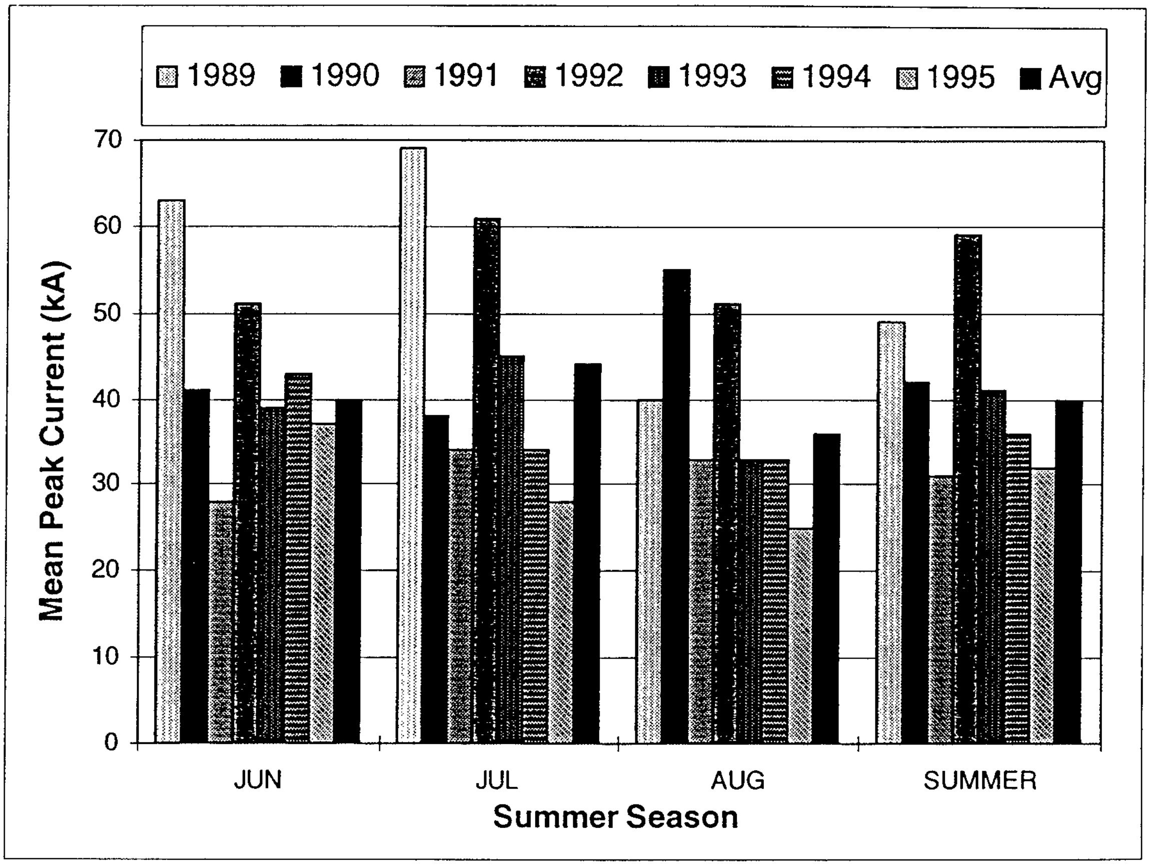

Figure 50. First stroke mean peak current for positive flashes during the summer season (June-August) from 1989 through 1995, and the overall average for each month. Seasonal average is included as well. Peak currents for 1995 consistently remain below average.

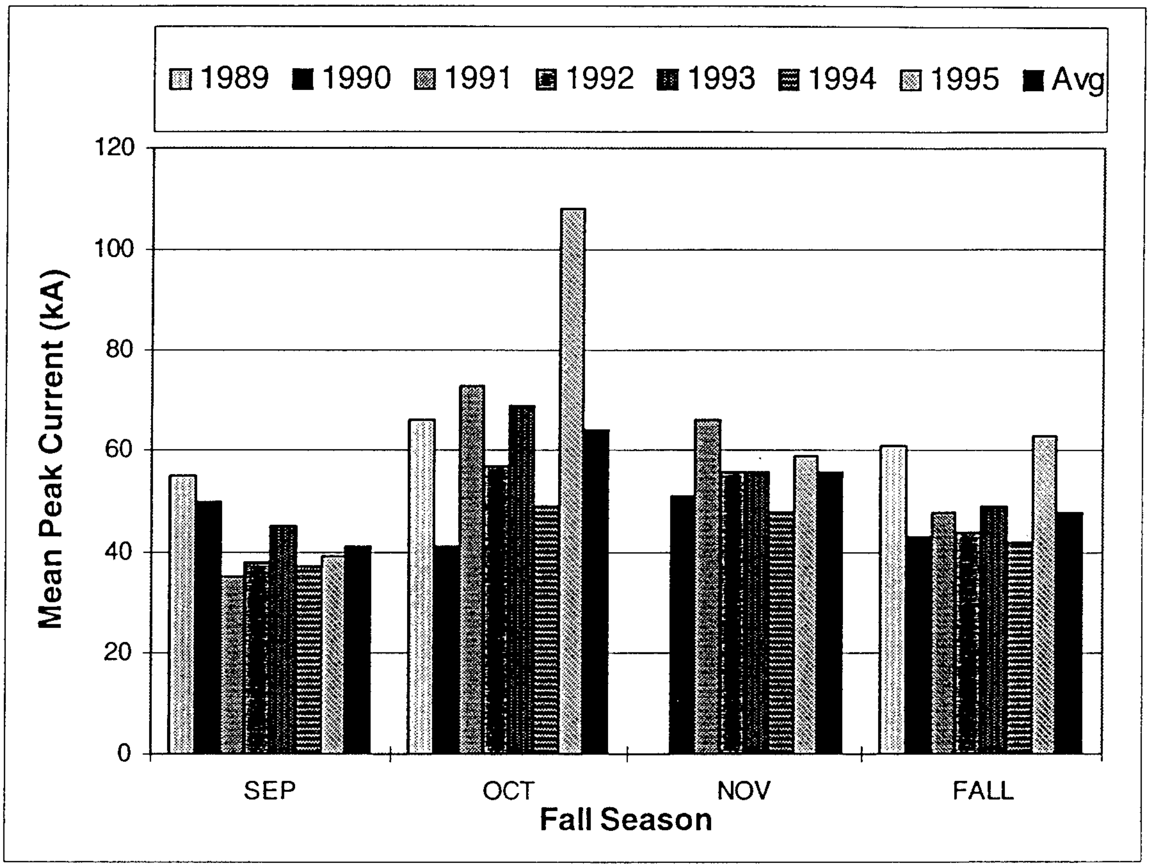

Figure 51. First stroke mean peak current for positive flashes during the fall season (September-November) from 1989 through 1995, and the overall average for each month. Seasonal average is included as well. Peak current for September 1995 was below average, but trend did not continue in October and November.

positive polarity. However, the mean peak current for positive flashes was 131 kA. In fact, 83 of the positive flashes had peak currents greater than 150 kA and 17 had currents greater than 200 kA. This particular storm was also responsible for the high average peak current for the month of October seen in Figure 48.

The meteorological conditions in the region before this activity occurred gave no indication of thunderstorms. An upper-level trough was located over the Tennessee Valley, with a ridge over the central Plains. A weak frontal system was along the Arkansas-Missouri border, and some weak thunderstorm activity was occurring south of this area. No precipitation was occurring north of the boundary. The temperature at 0600 UTC at Whiteman AFB was 11° C, with mostly cloudy skies. The 0000 UTC soundings from both Topeka and Springfield showed stable conditions, with Showalter stability indices greater than +7, lifted indices greater than +4.5, and K indices less than 14 at both locations. Furthermore, the atmosphere was dry through the mid-levels, with precipitable water only about half an inch through 500 millibars. In fact, Whiteman AFB measured only 0.11 of an inch of precipitation for the event. The first lightning flash was detected in west-central Missouri about 0730 UTC. Over the next several hours, a small MCS with an embedded east-west line of thunderstorms remained nearly stationary over the area. Cloud tops were measured up to 13 km at 1230 UTC, although most tops were between 10-12 km. Although no widespread power outages were confirmed, hailstones up to 1 inch reportedly covered the ground in several locations just to the east of the study area (Jim Angel, Midwestern Climate Center, personal communication, 1996).

All positive flashes were also compared against designated increments of peak currents (Table 8). The number of flashes measured that had peak currents less than 12 kA are in the first data column. Both 1994 and 1995 had many more flashes than the other years. This tendency continued for the number of flashes between each increment up to 60 kA. Only the number of flashes recorded in 1993 were comparable. Overall, more than half of all positive flashes with peak currents less than 30 kA recorded during the seven year period were reported in 1994 and 1995. The last column shows the number of flashes greater than 60 kA. Although 1994 had many more flashes than any other year, 1995 did not. However, the number of flashes for 1995 was still comparable

Table 8. The number of positive polarity cloud-to-ground lightning flashes during 1989 through 1995 that had first stroke peak currents (in kA) between designated threshold increments.

	PEAK CURRENT DESIGNATED INCREMENT					
YEAR	<12 kA	12<=x<20kA	20<=x<30 kA	30<=x<45 kA	45<=x<60 kA	>=60 kA
1989	115	262	366	525	465	974
1990	456	887	735	828	544	1241
1991	304	585	450	534	391	834
1992	149	438	648	928	700	1388
1993	387	1003	1407	1496	913	1691
1994	787	1163	1234	1561	1113	2209
1995	746	2560	1865	1624	850	1262
TOTAL	2944	6898	6705	7496	4976	9599

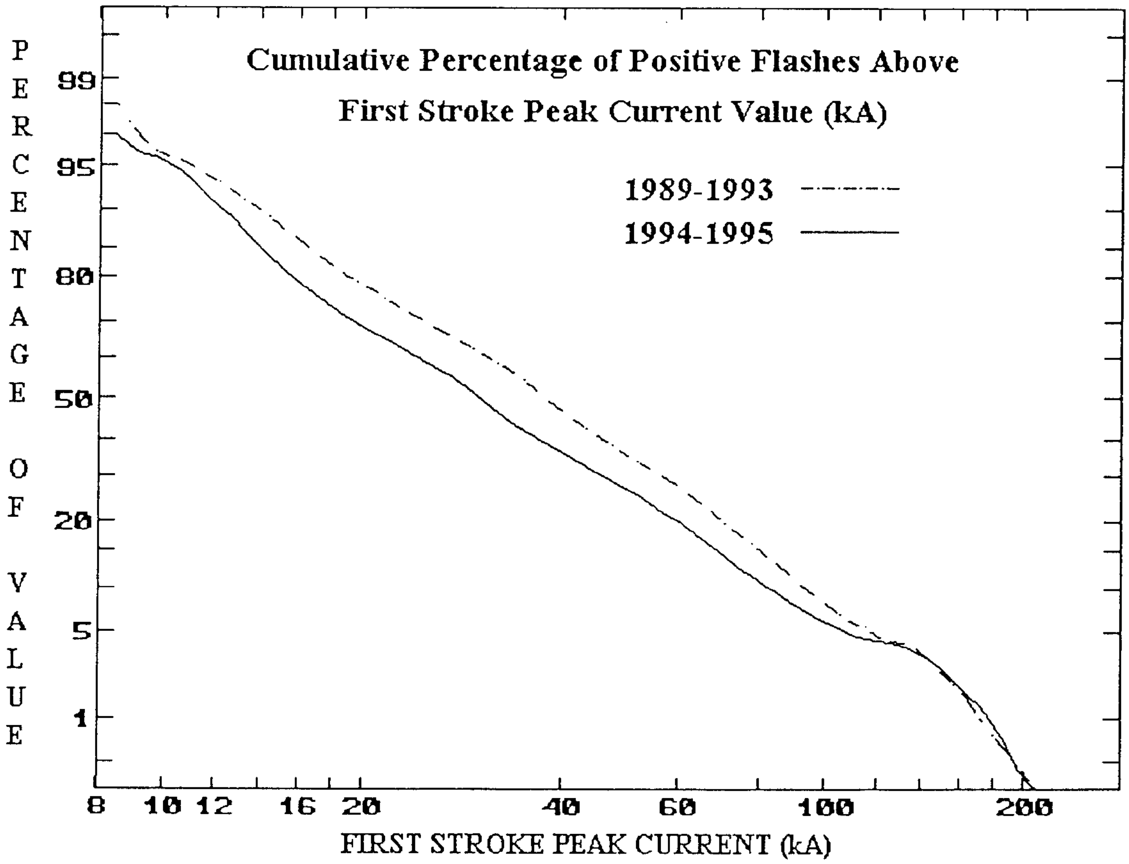

Figure 52. Cumulative percentage of all positive cloud-to-ground lightning flashes above first stroke peak current values (kA) for two data sets: 1989 through 1993, and 1994 through 1995.

to the average.

Finally, the cumulative percentage of positive flashes above first stroke peak current values are given in Figure 52. Once again, the dashed line is for all positive flashes recorded from 1989 through 1993, while the solid line represents all positive flashes recorded in 1994 and 1995. About 50% of all positive flashes recorded from 1989 through 1993 were above 40 kA. For 1994 and 1995, less than 40% of all positive flashes had peak currents greater than 40 kA. Similar to Figure 47, the solid line is continually below the dashed line until currents reach 150 kA, showing that a higher percentage of lower peak currents flashes are being detected since the upgrade of the NLDN.

In conclusion, a sharp increase in the number of negative CG lightning flashes with peak currents less than 20 kA was seen during the warm seasons of 1994 and 1995. Little if any increase in the number of flashes with currents greater than 20 kA was seen. Although it is certain that the NLDN is detecting more negative flashes of lower peak current, there still exists the possibility that a large percentage of the increase could be due to the network detecting intracloud flashes.

An increase was also observed in the amount of positive flashes as well, with a large increase in the number of flashes with currents less than 30 kA. A smaller but noticeable increase was seen in the number of positive flashes with peak currents greater than 30 kA. The increase in detection of positive flashes over a wide range of currents, and the increase in the percentage of positive lightning observed during 1994 and 1995, suggest that the detection efficiency of the NLDN has indeed increased for positive flashes.

2. Decision model method

a. Stability index and thermodynamic variable correlations

Before regression equations to predict thunderstorms can be formulated, many stability indices and thermodynamic variables must be studied, compared, and evaluated to ascertain which indices are most useful for forecasting thunderstorm development. Ten stability indices and two thermodynamic variables derived from soundings taken at both Monett and Topeka were selected for analysis. See Appendix for definitions and formulas for each of these variables. Linear correlation coefficients for each variable, that evaluate

their relationship to thunderstorm occurrence in the study area, were determined on a seasonal basis.

Table 9 lists the 12 indices and variables and their linear correlation coefficients for the three seasons for both Monett and Topeka soundings. Negative correlation coefficients imply that the lifted index (LI) and Showalter stability index (SSI) are indices of stability, while positive correlation coefficients imply that the remaining indices are indices of instability. Correlations for all variables at both locations were higher in the spring and fall than in the summer.

For Monett indices, LI had the strongest correlation for summer (-0.36) and fall (-0.55), and the second highest for the spring (-0.59). The Showalter stability index had the strongest correlation for the spring of -0.61. The Severe weather threat (SWEAT) index had the second highest correlation for both the summer and fall of 0.27 and 0.54, respectively. Vertical totals (VT) had the weakest correlation for both the summer (0.12) and fall (0.39). Contrary to Livingston's (1995) findings, CAPE 2000 had the weakest correlation for the spring (0.32), and the second weakest for both summer and fall of 0.18 and 0.40, respectively. CAPE had the second lowest correlation for the spring of 0.33.

For Topeka indices and variables, SSI was the most strongly correlated for the spring (-0.49) and second strongest for the summer (-0.29) and fall (-0.59). The K index (KI) had the highest correlation coefficients for both summer and fall, with values of 0.38 and 0.60, respectively. Lifted index was the second most strongly correlated index for the spring, at 0.46. On the other hand, CAPE was the most weakly correlated index for all three seasons with values of 0.25 for spring, 0.12 for summer, and 0.18 for fall. Vertical totals also had a correlation coefficient of 0.12 for summer. CAPE 2000 had the second lowest correlation for spring (0.26) and fall (0.19). CAPE 1000 recorded the same value of 0.19 for the fall season.

These correlation coefficients were derived from all non-thunderstorm and thunderstorm soundings. However, Table 5 showed that only 11 out of 122 (9%) category 1 and 2 events were reported at Whiteman AFB over the two year period. Since this study was mainly concerned with predicting thunderstorms at the base, correlation coefficients were determined comparing indices to only category 3 and 4 events and the

Table 9. Correlation coefficients comparing the values of the various indices and variables for non-thunderstorm periods to periods with thunderstorms. SSI stands for Showalter stability index. SWEAT is the severe weather threat index. CAPE is convective available potential energy. Sfc Theta-e is equivalent potential temperature at the surface. 925 Theta-e is equivalent potential temperature at 925 millibars. Spring is defined as March-May. Summer is defined as June-August. Fall is defined as September-November.

	MONETT				TOPEKA		
VARIABLE	SPRING	SUMMER	FALL		SPRING	SUMMER	FALL
SSI	-0.61	-0.26	-0.52		-0.49	-0.29	-0.59
K index	0.54	0.24	0.52		0.45	0.38	0.6
Lifted index	-0.59	-0.36	-0.55		-0.46	-0.28	-0.5
Total Totals	0.56	0.24	0.48		0.44	0.27	0.55
Cross Totals	0.49	0.22	0.42		0.37	0.27	0.56
Vert. Totals	0.49	0.12	0.39		0.34	0.12	0.33
SWEAT	0.5	0.27	0.54		0.45	0.28	0.49
CAPE	0.33	0.24	0.44		0.25	0.12	0.18
CAPE 1000	0.34	0.24	0.43		0.28	0.14	0.19
CAPE 2000	0.32	0.18	0.4		0.26	0.15	0.19
Sfc Theta-e	0.47	0.21	0.45		0.4	0.18	0.42
925 Theta-e	0.52	0.3	0.49		0.44	0.25	0.42

Table 10. Correlation coefficients comparing the values of the various indices and variables for non-thunderstorm periods to periods with thunderstorms that produced more than 100 cloud-to-ground lightning flashes (Category 3 and 4 events). Abbreviations and definitions are the same as in Table 9.

	MONETT (Cat 3-4 events)				TOPEKA (Cat 3-4 events)		
VARIABLE	SPRING	SUMMER	FALL		SPRING	SUMMER	FALL
SSI	-0.67	-0.29	-0.57		-0.55	-0.32	-0.61
K index	0.59	0.26	0.54		0.5	0.41	0.61
Lifted index	-0.65	-0.37	-0.62		-0.47	-0.3	-0.54
Total Totals	0.61	0.26	0.51		0.49	0.29	0.55
Cross Totals	0.54	0.25	0.45		0.41	0.3	0.56
Vert. Totals	0.52	0.13	0.39		0.38	0.11	0.31
SWEAT	0.63	0.33	0.62		0.51	0.33	0.56
CAPE	0.4	0.24	0.57		0.33	0.13	0.22
CAPE 1000	0.44	0.26	0.55		0.36	0.15	0.25
CAPE 2000	0.47	0.23	0.52		0.32	0.18	0.25
Sfc Theta-e	0.5	0.19	0.56		0.41	0.19	0.48
925 Theta-e	0.58	0.29	0.61		0.44	0.28	0.5

non-thunderstorm periods.

Table 10 shows the results of this effort. In almost every case, for all seasons and both sounding locations, the linear correlation coefficients were higher than the previous example. For Monett, the two best correlations for each season were for the same indices as the original run, but coefficients were about 0.06 higher per index per season. For Topeka, SWEAT replaced LI as the second strongest correlation during the spring, with a value of 0.51, and replaced SSI in the summer with a value of 0.33. The most strongly correlated indices in the spring and summer and the two most strongly correlated indices for the fall remained the same, but correlation coefficients increased about 0.03 per index.

Differences in the values of the indices between non-thunderstorm soundings and category 3 and 4 events were analyzed. Statistical values for the spring season are shown in Table 11 for both the Monett and Topeka data sets. The number of samples, the mean, and the median of all indices and variables for both non-thunderstorm soundings and category 3 and 4 soundings are given. In addition, the lower quartile values of variables are included for category 3 and 4 events. The lower quartile denotes the 25th percentile of a set. For this study, the lower quartile represented the value of an index or variable that 75% of the thunderstorms occurred at or above (at or below for SSI and LI). A large difference in the medians and means is apparent between thunderstorm and non-thunderstorm categories for almost every index. Statistical values for both locations for the summer and fall seasons are shown in Tables 12 and 13, respectively. Comparing the data for thunderstorm events over all three seasons showed that the values for each index were similar. In contrast, comparisons between seasons of the data for the non-thunderstorm periods shows that while the fall and spring seasons were comparable, the summer season values were very different. The variable values during the spring and fall seasons for non-thunderstorm events were much lower than those for thunderstorm events. On the other hand, the summertime values for non-thunderstorm events were close to those of the thunderstorm events. A seasonal difference in the atmosphere between the seasons was clearly apparent. The spring and fall seasons were marked by a typically stable atmosphere which was affected by frontal systems that produced unstable conditions, while the atmosphere in the summer season was generally unstable and only

Table 11. Number of samples, means, and medians of the 12 indices for category 3 and 4 events and all non-thunderstorm periods from the spring data sets for Monett and Topeka. Lower quartile values for category 3 and 4 events are also included.

MONETT SPRING DATA								
	CATEGORY 3 AND 4 EVENTS					NON-THUNDERSTORM PERIODS		
	NUMBER OF			LOWER		NUMBER OF		
VARIABLE	SAMPLES	MEAN	MEDIAN	QUARTILE		SAMPLES	MEAN	MEDIAN
SSI	48	-0.84	-0.93	0.75		80	8.23	8.73
K index	48	28	31	20.7		80	6.8	6.7
Lifted index	48	0.11	-0.9	2.42		80	8.73	9.87
Total Totals	48	50.5	50.4	47.7		80	37.1	38.5
Cross Totals	48	23.2	23.4	21.4		80	13.6	15.9
Vert. Totals	48	27.3	26.9	25.8		80	23.5	23.5
SWEAT	48	274	253	162		80	112	89
Sfc Theta-e	48	321	323	313		80	306	306
925 Theta-e	48	325	327	319		80	308	307
CAPE	48	252	142	0		80	36	0
CAPE 1000	48	243	127	0		80	30	0
CAPE 2000	48	147	40	0		80	11	0

TOPEKA SPRING DATA								
	CATEGORY 3 AND 4 EVENTS					NON-THUNDERSTORM PERIODS		
	NUMBER OF			LOWER		NUMBER OF		
VARIABLE	SAMPLES	MEAN	MEDIAN	QUARTILE		SAMPLES	MEAN	MEDIAN
SSI	33	0.94	0.35	3.97		79	7.88	8.12
K index	33	26.4	28.9	22.5		79	10.3	8.7
Lifted index	33	2.12	1.26	6.06		79	8.97	9.66
Total Totals	33	48.1	50	44.6		79	38.5	38.4
Cross Totals	33	21	21.9	19.1		79	14.5	14.9
Vert. Totals	33	27.2	27.1	24.8		79	24.1	24.2
SWEAT	33	228	203	158		79	110	89
Sfc Theta-e	33	319	323	308		79	304	303
925 Theta-e	33	321	321	309		79	307	305
CAPE	33	336	1	0		79	48	0
CAPE 1000	33	330	0	0		79	38	0
CAPE 2000	33	210	0	0		79	21	0

Table 12. Number of samples, means, and medians of the 12 indices for category 3 and 4 events and all non-thunderstorm periods from the summer data sets for Monett and Topeka. Lower quartile values for category 3 and 4 events are also included.

MONETT SUMMER DATA								
	CATEGORY 3 AND 4 EVENTS					NON-THUNDERSTORM PERIODS		
VARIABLE	NUMBER OF SAMPLES	MEAN	MEDIAN	LOWER QUARTILE		NUMBER OF SAMPLES	MEAN	MEDIAN
SSI	109	-1.06	-1.82	0.24		79	1.41	0.52
K index	109	29.9	32.6	24.1		79	24.2	26.1
Lifted index	109	-2.75	-3.02	-1.45		79	-0.06	-1.08
Total Totals	109	47.5	48.2	45.2		79	44.3	46.2
Cross Totals	109	20.8	21.6	19.5		79	18.3	19.1
Vert. Totals	109	26.6	26.5	25.1		79	26	26.1
SWEAT	109	241	233	194		79	186	190
Sfc Theta-e	109	344	344	338		79	340	339
925 Theta-e	109	346	347	342		79	340	341
CAPE	109	1120	980	406		79	685	310
CAPE 1000	109	956	819	307		79	527	183
CAPE 2000	109	439	271	30		79	223	16

TOPEKA SUMMER DATA								
	CATEGORY 3 AND 4 EVENTS					NON-THUNDERSTORM PERIODS		
VARIABLE	NUMBER OF SAMPLES	MEAN	MEDIAN	LOWER QUARTILE		NUMBER OF SAMPLES	MEAN	MEDIAN
SSI	104	-1.79	-1.74	0.4		74	1.17	0.19
K index	104	32.9	35	29.9		74	24.1	26.6
Lifted index	104	-2.7	-2.81	-0.71		74	-0.14	-0.88
Total Totals	104	48.6	48.3	46		74	45	46.8
Cross Totals	104	21.5	21.9	19.7		74	18.4	19.4
Vert. Totals	104	27.1	26.9	25.6		74	26.5	26.9
SWEAT	104	273	249	197		74	200	191
Sfc Theta-e	104	344	344	337		74	339	338
925 Theta-e	104	345	346	341		74	338	336
CAPE	104	1130	808	117		74	818	259
CAPE 1000	104	1032	749	178		74	720	231
CAPE 2000	104	670	332	57		74	405	16

Table 13. Number of samples, means, and medians of the 12 indices for category 3 and 4 events and all non-thunderstorm periods from the fall data sets for Monett and Topeka. Lower quartile values for category 3 and 4 events are also included.

MONETT FALL DATA								
	CATEGORY 3 AND 4 EVENTS					NON-THUNDERSTORM PERIODS		
	NUMBER OF			LOWER		NUMBER OF		
VARIABLE	SAMPLES	MEAN	MEDIAN	QUARTILE		SAMPLES	MEAN	MEDIAN
SSI	38	0.06	-0.6	1.42		64	7.74	8.31
K index	38	29.2	31.7	25.6		64	10	10.6
Lifted index	38	-0.43	-1.16	1.9		64	8.3	7.84
Total Totals	38	46.5	46.8	44.4		64	35.9	37.4
Cross Totals	38	21	22.1	20.1		64	13.1	16.1
Vert. Totals	38	25.4	25.4	23.1		64	22.8	22.9
SWEAT	38	263	254	196		64	125	116
Sfc Theta-e	38	333	333	324		64	313	314
925 Theta-e	38	336	336	328		64	315	316
CAPE	38	623	343	0		64	24	0
CAPE 1000	38	529	217	1		64	29	0
CAPE 2000	38	265	67	1		64	13	0

TOPEKA FALL DATA								
	CATEGORY 3 AND 4 EVENTS					NON-THUNDERSTORM PERIODS		
	NUMBER OF			LOWER		NUMBER OF		
VARIABLE	SAMPLES	MEAN	MEDIAN	QUARTILE		SAMPLES	MEAN	MEDIAN
SSI	33	0.43	0.16	2.38		64	8.51	9.08
K index	33	28.9	29.9	23.6		64	8.8	8.5
Lifted index	33	0.98	0.91	3.27		64	8.65	9.02
Total Totals	33	47.1	46.9	44.2		64	36	37
Cross Totals	33	21.5	21.6	19.8		64	12.9	13.7
Vert. Totals	33	25.7	25.9	23.9		64	23.1	22.8
SWEAT	33	251	231	171		64	122	107
Sfc Theta-e	33	328	325	319		64	311	310
925 Theta-e	33	330	330	319		64	313	316
CAPE	33	313	1	0		64	89	0
CAPE 1000	33	305	1	0		64	81	0
CAPE 2000	33	208	4	0		64	43	0

needed some type of trigger, such as a trough or differential heating to initiate thunderstorm activity.

In the next section, the best of these 12 indices will be used to develop regression equations. These equations will be a significant part of the decision model to predict thunderstorm occurrence at Whiteman AFB.

b. Regression analysis

Linear regression equations were developed using seasonal data sets obtained from Monett and Topeka soundings for March through November of 1993 and 1994. A total of six equations were developed, one for each season and location. The regression models were formulated to differentiate category 3 and 4 thunderstorm periods from non-thunderstorm periods, but were tested against the entire data set for that particular season. Skill scores were determined for each test using the critical success index (CSI), false alarm rate (FAR), probability of detection (POD), and Yule's index (YI). A summary and equations for these skill scores are found in the Appendix.

Variables obtained from the Monett soundings for spring produced the following regression equation:

$$A = -.2905 - .0134(SSI) - .052(LI) + .00257(SWEAT) \qquad (1)$$

The numbers are the parameter estimates of the intercept, SSI, LI, and SWEAT index. The values for the three indices are the analyzed values taken directly from a sample sounding. The equation produces a positive number when low or negative values of SSI and LI and high values of SWEAT (all indicators of the potential for thunderstorms) are inserted. Equation (1) thus assigns positive values to "A" for samples with strong thunderstorm potential, and negative values to "A" for weak potential.

Table 14 shows the results of equation (1) tested on the dependent data set for the spring of 1993 and 1994. Of the 48 category 3 and 4 thunderstorm periods, the model correctly predicted 40. Similarly, the model correctly predicted 69 of the 80 non-thunderstorm periods. The CSI for the model was 68%, while YI was 0.69. The POD was 83%, while the FAR was 22%.

Figures 53a and 53b are histograms giving an example of the output from equation (1) for thunderstorm and non-thunderstorm periods, respectively. Responses for the

Table 14. Contingency table showing prediction results for equation (1) on the dependent data set from Monett for the spring seasons of 1993 and 1994. TSTM stands for thunderstorm. The equation correctly predicted 109 of 128 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	40	8	48
OBSERVED NO TSTM	11	69	80
TOTAL	51	77	128

Table 15. Same as Table 14, except on the independent data set from Monett for the spring season of 1995. The equation correctly predicted 68 of 77 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	13	2	15
OBSERVED NO TSTM	7	55	62
TOTAL	20	57	77

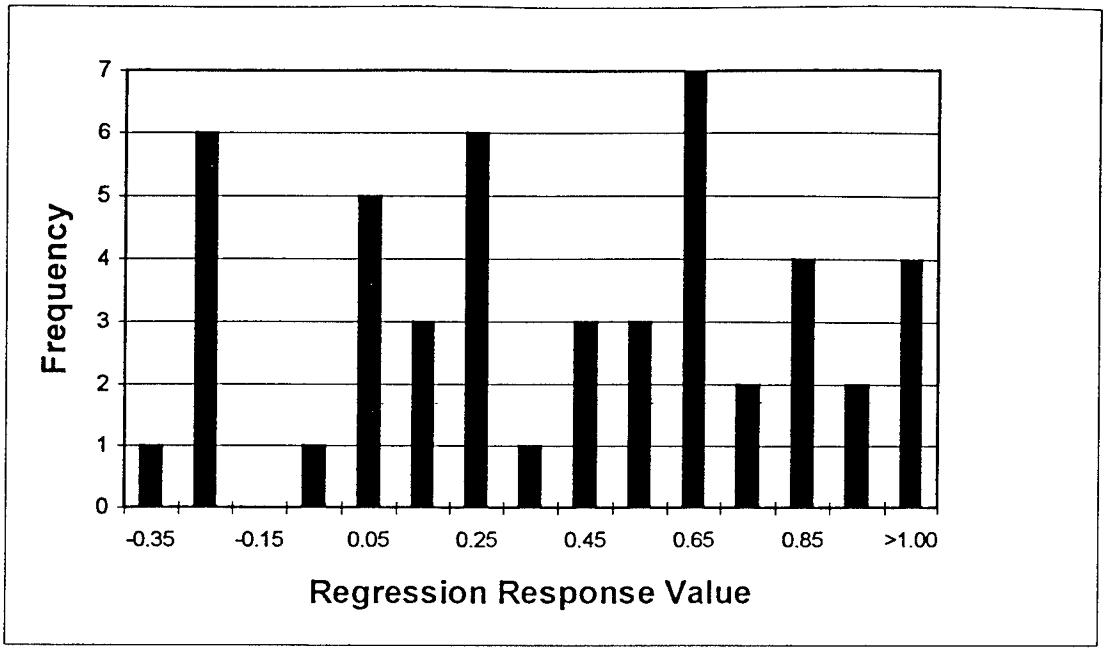

Figure 53a. Histogram of responses from equation (1) on category 3 and 4 thunderstorm periods for the spring season dependent data set from Monett. Only eight responses were negative.

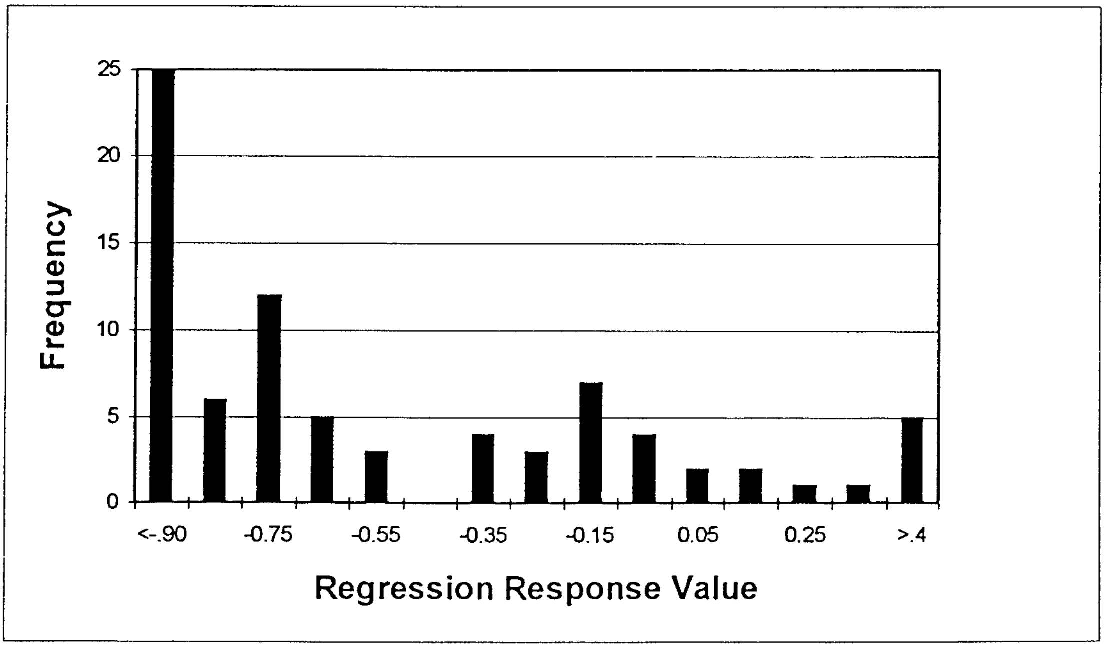

Figure 53b. Same as Figure 53a, except for responses of non-thunderstorm periods. Only 11 responses were positive.

thunderstorm periods were concentrated in the positive numbers, while responses for the non-thunderstorm periods were concentrated on the negative side. The negative responses for the thunderstorm periods were all greater than -0.40, while 51 of the 80 non-thunderstorm responses were below -0.40. Similarly, only four responses for non-thunderstorm periods were above +0.40, while 25 of 48 thunderstorm responses were above +0.40.

Equation (1) was then tested on data for the category 1 and 2 events that had been excluded when the model was developed. Of the 32 events, only 14 were correctly predicted by the equation. This was not totally unexpected since the indices during those periods tended to indicate more stable conditions than most category 3 and 4 events, yet less stable conditions than most non-thunderstorm periods.

Finally, equation (1) was tested against an independent data set. Seventy-seven samples were selected from the Spring of 1995 from Monett and Springfield using the stratified random sampling technique. During May of 1995, the rawinsonde location was moved from Monett to Springfield, a move of approximately 65 km to the east-northeast. Thus, samples were taken from both locations for the spring season, and only at Springfield afterwards. No difference in the responses from the regression equation due to the change in locations was noticed. The results of the verifications on the 1995 data are shown in Table 15. Only two of 15 thunderstorm periods were not predicted, for a POD of 87%. The model also incorrectly forecast seven of 62 non-thunderstorm periods. Overall, the CSI was 59%, the YI was 0.68, and the FAR was 35%.

The procedure was followed again for Topeka. Variables obtained from the Topeka soundings during spring produced the following regression equation:

$$B = -.6801 - .029(SSI) + .0127(KI) + .00237(SWEAT) \qquad (2)$$

In this case, KI replaced LI as one of the independent variables in the equation. Otherwise, equation (2) acts the same way as equation (1), with positive values assigned to "B" for samples with thunderstorm potential, and negative values assigned to "B" for samples with weak potential.

The results of equation (2) tested on the dependent data set for the spring of 1993 and 1994 are shown in Table 16. Of the 33 category 3 and 4 thunderstorm periods, the

Table 16. Contingency table showing prediction results for equation (2) on the dependent data set from Topeka for the spring seasons of 1993 and 1994. TSTM stands for thunderstorm. The equation correctly predicted 92 of 112 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	23	10	33
OBSERVED NO TSTM	10	69	79
TOTAL	33	79	112

Table 17. Same as Table 16, except on the independent data set from Topeka for the spring season of 1995. The equation correctly predicted 67 of 77 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	12	3	15
OBSERVED NO TSTM	7	55	62
TOTAL	19	58	77

model correctly predicted 23. The model missed 10 of the 79 non-thunderstorm periods. The regression equation had a CSI of 54%, POD of 70%, FAR of 30%, and a YI of 0.57.

Equation (2) was then tested on the category 1 and 2 events that had been excluded. Only 10 of 31 events were correctly predicted by the model. Again, this poor showing was due to the fact that the stability indices during those periods tended to indicate more stable conditions than most category 3 and 4 events, but less stable conditions than most non-thunderstorm periods.

Table 17 shows how equation (2) performed on an independent data set. This data set consisted of 77 samples selected from Topeka soundings during the Spring of 1995. Only three thunderstorm periods and seven non-thunderstorm periods were forecast incorrectly, for a CSI of 55%, POD of 80%, FAR of 37%, and a YI of 0.63.

Regression models were then tested for the summer season. As mentioned earlier, numerous problems were encountered with the initial regression equations for Monett. Therefore, the regression procedures were forced to accept the K index and then allowed to formulate an equation. The equation which performed the best in subsequent tests was the following:

$$C = -.399 + .00575(KI) - .0681(LI) + .00133(SWEAT) \qquad (3)$$

As expected, equation (3) did not perform as well as the previous models on either the dependent data set or the independent data set. Table 18 lists the results of the model test on the dependent data set for the summer of 1993 and 1994. The equation had a bias to over-predict thunderstorms. Of the 109 thunderstorm periods, only 16 were not predicted by the model, for a POD of 85%. However, 42 of 79 observed non-thunderstorm periods were forecast as thunderstorm periods by equation (3). The high number of thunderstorm periods forecast correctly in relation to the total number of samples gave an artificially high CSI of 62% and a FAR was 31%. Yule's Index, which takes into account the overall prediction of both thunderstorm and non-thunderstorm periods, gave a better indication of the total accuracy of the model with a score of 0.35.

Against the category 1 and 2 events, equation (3) performed better than equations (1) and (2). Of the 57 events, 46 were correctly forecast. Since most days in the summer exhibit typically unstable conditions this performance was not totally surprising.

Table 18. Contingency table showing prediction results for equation (3) on the dependent data set from Monett for the summer seasons of 1993 and 1994. TSTM stands for thunderstorm. The equation correctly predicted 130 of 188 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	93	16	109
OBSERVED NO TSTM	42	37	79
TOTAL	135	53	188

Table 19. Same as Table 18, except on the independent data set from Monett for the summer season of 1995. The equation correctly predicted 54 of 77 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	28	5	33
OBSERVED NO TSTM	18	26	44
TOTAL	46	31	77

Equation (3) was then tested on the independent data set made from Springfield soundings during the Summer of 1995. Again, 77 samples were selected at random, 33 of which were thunderstorm periods. The classification table of results is shown in Table 19. In this test, the equation performed slightly better than it did against the dependent data set. Yule's index increased to 0.44, primarily because only 18 of 44 non-thunderstorm events were forecast incorrectly. Compared to the test on the dependent data set, CSI decreased to 55%, the FAR increased to 39%, and the POD remained the same at 85%.

Variables obtained from the Topeka soundings for summer produced the following regression equation:

$$D = -1.0347 + .0316(KI) + .00115(SWEAT) \qquad (4)$$

This equation was the only one to use only two independent variables. Nevertheless, the equation performed the same way as the other five equations, producing a positive number for a thunderstorm period prediction.

Equation (4) was similar to equation (3) in terms of its performance on its dependent data set (see Table 20). Eighty-nine of 104 thunderstorm periods were forecast correctly, for a POD of 86%. Exactly half (37 of 74) of the non-thunderstorm periods were forecast incorrectly, for a FAR of 29%. The CSI was high at 63%, while YI was only 0.39. Against category 1 and 2 data from the summers of 1993 and 1994 for Topeka, 40 out of 51 events were forecast correctly.

Seventy-five were utilized from Topeka during the Summer of 1995, comprising the independent data set. The results presented in Table 21 show that of the 32 thunderstorm periods, 28 were correctly predicted by equation (4). In addition, 27 of the 43 non-thunderstorm periods were forecast correctly. Skill scores for this test consisted of a CSI of 58%, a FAR of 36%, a POD of 88%, and a YI of 0.51.

Regression models were formulated and tested for the fall season. Variables from the Monett soundings for fall produced the following equation:

$$E = -1.08 - .0062(SSI) + .0108(KI) + .00407(SWEAT) \qquad (5)$$

The results of the verification of equation (5) on the dependent data set developed from the fall seasons of 1993 and 1994 are shown in Table 22. Nine of the 38 category 3 and 4 thunderstorm periods were incorrectly predicted, as were nine of the 64 non-thunderstorm

Table 20. Contingency table showing prediction results for equation (4) on the dependent data set from Topeka for the summer seasons of 1993 and 1994. TSTM stands for thunderstorm. The equation correctly predicted 126 of 178 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	89	15	104
OBSERVED NO TSTM	37	37	74
TOTAL	126	52	178

Table 21. Same as Table 20, except on the independent data set from Topeka for the summer season of 1995. The equation correctly predicted 55 of 75 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	28	4	32
OBSERVED NO TSTM	16	27	43
TOTAL	44	31	75

Table 22. Contingency table showing prediction results for equation (5) on the dependent data set from Monett for the fall seasons of 1993 and 1994. TSTM stands for thunderstorm. The equation correctly predicted 84 of 102 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	29	9	38
OBSERVED NO TSTM	9	55	64
TOTAL	38	64	102

Table 23. Same as Table 22, except on the independent data set from Monett for the fall season of 1995. The equation correctly predicted 50 of 60 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	10	2	12
OBSERVED NO TSTM	8	40	48
TOTAL	18	42	60

periods. This translates into skill scores of a CSI of 62%, a FAR of 24%, a POD of 76%, and a YI of 0.62.

Of the 23 category 1 and 2 events that occurred over the two fall seasons, the model correctly predicted 13. While the probability of detection was higher than for the category 1 and 2 events for the spring period, the prediction results were still far worse than for the both the category 3 and 4 events and the non-thunderstorm periods.

Sixty samples were selected from Springfield soundings during the fall of 1995 to make up the independent data set used for testing equation (5). Only two of 12 thunderstorm periods were incorrectly predicted for a POD of 83% (Table 23). However, eight of the 48 non-thunderstorm periods were forecast as thunderstorm periods for a FAR of 44%. Additionally, the CSI was 50%, while YI was 0.58.

The same indices were selected for the Topeka fall regression equation, with differences in the parameter estimates. The regression equation was:

$$F = -.7347 - .029(SSI) + .0185(KI) + .00177(SWEAT) \qquad (6)$$

The last equation was tested against its dependent data set derived from Topeka soundings during the falls of 1993 and 1994. Table 24 reveals that of the 33 thunderstorm periods, 24 were predicted correctly, while 57 of 64 non-thunderstorm periods were predicted correctly. The YI for this test was 0.63, the CSI was 60%, the FAR was 23%, and the POD was 73%.

Only 18 category 1 and 2 events were sampled from Topeka soundings over the two fall seasons. Of those, equation (6) correctly predicted 10.

Finally, equation (6) was tested against an independent data set derived from Topeka soundings from the Fall of 1995. In this case, 58 soundings were used, including the same 12 thunderstorm periods recorded in the independent data set used to test equation (5). Nine of these 12 periods were forecast correctly by equation (6) (see Table 25) for a POD of 75%. Only six of 46 non-thunderstorm periods were forecast as thunderstorm periods for a FAR of 40%. The CSI was 50% and YI was 0.57.

In the next section, the results of the two individual equations for each season were combined with one another in a decision method to further improve the forecasting accuracy of thunderstorms at Whiteman AFB. Other significant factors such as frontal

Table 24. Contingency table showing prediction results for equation (6) on the dependent data set from Topeka for the fall seasons of 1993 and 1994. TSTM stands for thunderstorm. The equation correctly predicted 81 of 97 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	24	9	33
OBSERVED NO TSTM	7	57	64
TOTAL	31	66	97

Table 25. Same as Table 24, except on the independent data set from Topeka for the fall season of 1995. The equation correctly predicted 49 of 58 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	9	3	12
OBSERVED NO TSTM	6	40	46
TOTAL	15	43	58

locations were also included.

c. Decision method

By themselves, each regression equation was a good first guess for thunderstorm prediction. However, by combining the results of both equations for each season, and considering several other factors important for thunderstorm generation in that area, an even better prediction was made.

In the previous section, each regression equation was tested on an independent data set of 1995 sounding data. The results of the two equations for each season were compared to examine their similarities and differences. The matrix that resulted from comparing the answers of equation (1) and equation (2) together for each individual sample taken from Spring 1995 is shown in Table 26. In 12 of the sampled periods, both regression equations predicted thunderstorms, 10 of which verified. In 49 other samples, both equations predicted no thunderstorms. In each case, no thunderstorms occurred in the study area. However, in 16 cases, one equation predicted yes while the other predicted no. A method was needed to decide whether to forecast thunderstorm activity.

In each of the 16 cases, analysis was done on each individual sounding, as well as on standard weather charts available for those time periods. Unfortunately, threshold values of different indices and variables were not reliable decision making tools. A quick and reliable product which proved useful for determination was a surface analysis map available from near the sounding time. The following illustration details how the 16 incidents were resolved by examining the soundings, especially low-level temperatures, moisture, and winds, in conjunction with a surface analysis map.

In all 16 cases, a frontal boundary or trough was within 200 km of at least one of the sounding locations. In four of the nine cases in which equation (1) was positive and equation (2) negative, the front had passed by Topeka and was either through or almost through the study region, but had not passed over Monett. These cases all verified negative. In four of those five remaining cases, the frontal boundary was also between the two sounding locations. However, on one occasion, a strong front was not yet in the study area, whose airmass was similar to Monett's. Thunderstorms occurred. In the other three cases, the boundary was south of the study area, but moved north as a warm front.

Table 26. Matrix of the number of responses for equations (1) and (2) against the same sample periods from the Spring 1995 data set. Abbreviations: TSTM - thunderstorm; pos - positive response value; neg - negative response value. On no occasions did thunderstorms occur when both equations gave negative responses.

	BOTH POS	(1) POS - (2) NEG	(1) NEG - (2) POS	BOTH NEG
OBSERVED TSTM	10	3	2	0
OBSERVED NO TSTM	2	6	5	49
TOTAL	12	9	7	49

In two of these events, thunderstorms occurred in the region. In the other case, severe thunderstorms occurred just north of the area after the front exited the region. Finally, for the last of the nine cases, a cold front was located south of Springfield. Overrunning kept the sounding unstable enough to produce the positive response, but the study area airmass was more comparable to that of Topeka.

On seven occasions, equation (2) had a positive response while equation (1) was negative. In three out of six cases, a frontal boundary or trough was near Topeka, destabilizing the atmosphere enough to cause a positive response. However, these boundaries were all well away from the area of interest, and would not be affecting the region during that forecast period. All three cases verified no. In one of the three remaining cases, a surface trough was just west of Topeka, but close enough to move into the study region during the forecast period. For one of the remaining two events, both soundings showed unstable conditions due to a strong surface front, but a weak lifted index at Monett prevented equation (1) from being positive. Both of these cases verified yes. In the final case, a weak warm front was between the study area and Topeka. The front pushed northeast and died out, but outflow boundaries from other thunderstorms pushed into the area from the northwest. However, no thunderstorms were triggered.

Using these 16 examples as a guide, a decision method for forecasting thunderstorms at Whiteman AFB was developed. This model is displayed in Figure 54. Because the spring and fall seasons were somewhat similar as far as thunderstorm occurrence was concerned, this decision method was used for both of seasons. An explanation of each step follows.

At decision step 1, the user is asked to insert the values for the appropriate indices from a sounding taken at Springfield into equation (1) or (5), depending on the season. Regardless of the answer, steps 2 or 4 both ask the user to insert the appropriate index values from a Topeka sounding into equation (2) or (6). If both equations give a negative response, step 3 says to forecast no thunderstorms. If both equations give a positive response, step 7 says to forecast thunderstorms at the station. However, if one equation is positive and the other negative, the forecaster proceeds to step 5. This step is where the most recent surface analysis chart should be employed. Step 5 asks if a frontal boundary

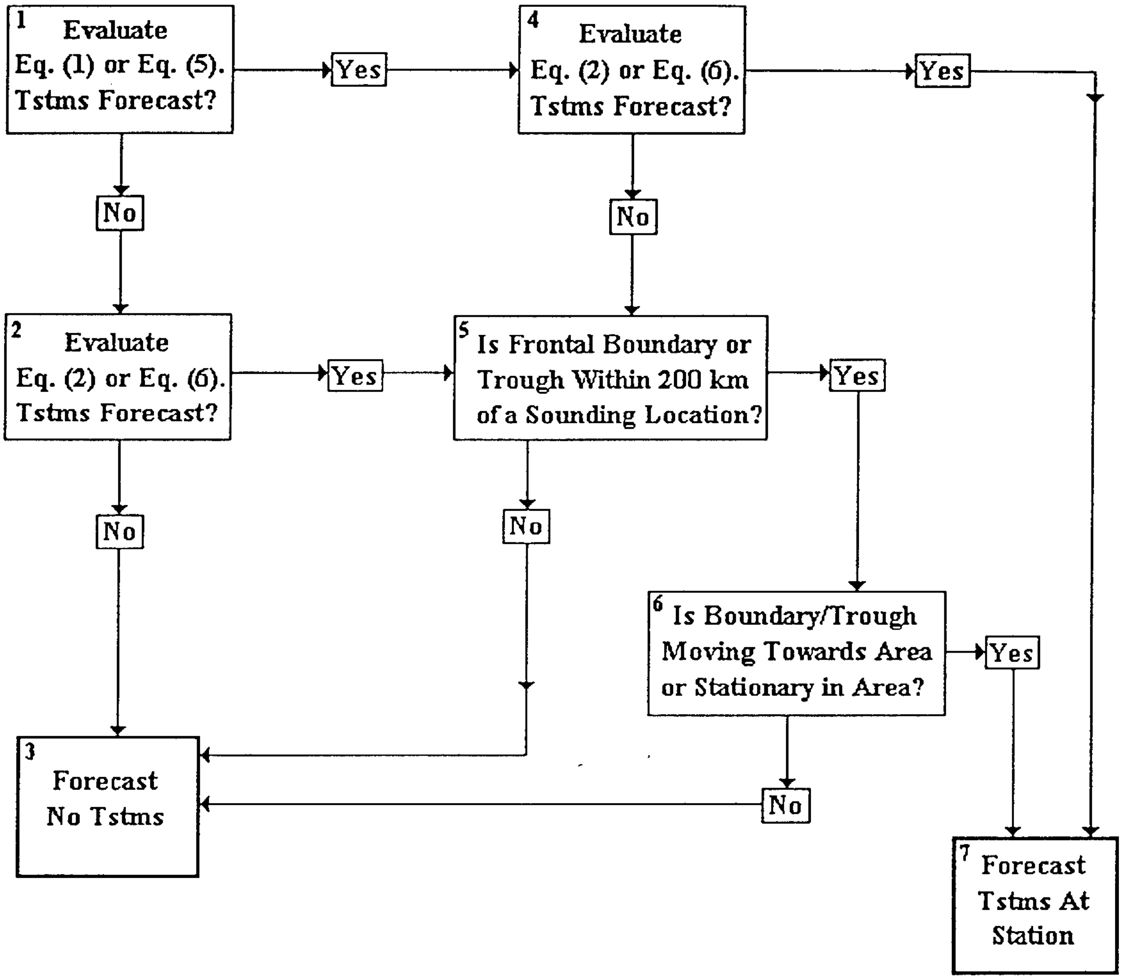

Figure 54. Thunderstorm decision model for the spring or fall seasons at Whiteman Air Force Base.. Abreviations in the figure: Eq. - equation; Tstms - thunderstorms. Equations (1) and (2) are to be used during the spring. Equations (5) and (6) are to be used during the fall.

or trough is within 200 km of either sounding location, regardless of whereabouts. Thunderstorms are typically uncommon in the spring and fall over west-central Missouri without aid of a front or trough. Thus, if the answer to step 5 is no, the forecaster is then advised by step 3 not to forecast thunderstorms. On the other hand, if a front or trough is in the area, the user is sent to step 6. This decision step asks whether the boundary is moving towards the area, or is currently stationary over the region. If the boundary is moving away, conditions should become more stable, thus no thunderstorms would be expected. If the answer to step 6 is yes, that a boundary is moving towards or remaining in the area, then thunderstorms would be forecast.

Table 27 shows the results of using the decision model on the data set from Spring, 1995. Admittedly, these results may be somewhat biased since the model was derived from this set. Of the 16 yes/no cases, 14 verified correctly by determining if there was a frontal boundary or trough in the area and determining which way it was moving. Of these 14, nine verified no, while the other five verified yes. For the two remaining cases, thunderstorm forecasts verified no, and gave false alarm results. The skill scores for this decision method were: CSI=79%, POD=100%, FAR=21%, and YI=0.86.

The data from Fall, 1995 was then tested using the decision model. Table 28 is the matrix of results by comparing the answers from equations (5) and (6). Since two sample periods were missing from Topeka, the responses from equation (5) on the Springfield data were used as the overall result for those samples. Seven correct thunderstorm predictions were made, with four false alarms. Thirty-seven non-thunderstorm predictions were made, with no thunderstorms occurring. Twelve of the 60 samples gave a yes/no result. Table 29 is the classification table of the results when the decision model was used. Of the twelve thunderstorm occurrences, 11 were predicted by the model. Similarly, 42 out of 48 non-thunderstorm periods were correctly predicted. The results gave a CSI of 61%, a FAR of 35%, a POD of 92%, and a YI of 0.70. Once again, improvement was seen in all skill scores when compared to the scores for the individual equations.

Table 30 shows the matrix of comparing responses of equations (3) and (4) for the 1995 summer season data set. Of the 36 cases in which both equations gave a positive response, 24 verified for thunderstorms. Similar to the spring and fall season results, no

Table 27. Contingency table showing prediction results using the decision model in Figure 54 on the spring data set from 1995. TSTM stands for thunderstorm. The model correctly predicted 73 of 77 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	15	0	15
OBSERVED NO TSTM	4	58	62
TOTAL	19	58	77

Table 28. Matrix of the number of responses for equations (5) and (6) against the same sample periods from the Fall 1995 data set. Abbreviations: TSTM - thunderstorm; pos - positive response value; neg - negative response value. On no occasions did thunderstorms occur when both equations gave negative responses.

	BOTH POS	(1) POS - (2) NEG	(1) NEG - (2) POS	BOTH NEG
OBSERVED TSTM	7	3	2	0
OBSERVED NO TSTM	4	4	3	37
TOTAL	11	7	5	37

Table 29. Contingency table showing prediction results using the decision model in Figure 54 on the fall data set from 1995. TSTM stands for thunderstorm. The model correctly predicted 53 of 60 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	11	1	12
OBSERVED NO TSTM	6	42	48
TOTAL	17	43	60

Table 30. Matrix of the number of responses for equations (3) and (4) against the same sample periods from the Summer 1995 data set. Abbreviations: TSTM - thunderstorm; pos - positive response value; neg - negative response value. Once again, there were no occasions of thunderstorm occurrence when both equations gave negative responses.

	BOTH POS	(1) POS - (2) NEG	(1) NEG - (2) POS	BOTH NEG
OBSERVED TSTM	24	4	5	0
OBSERVED NO TSTM	12	6	5	21
TOTAL	36	10	10	21

thunderstorms occurred when both equations gave a negative response, with 21 cases verifying no. This left 20 cases with one positive and one negative response.

In one of the 20 cases, equation (4) gave a positive response because of an abnormally high K index. Otherwise, the sounding was moderately stable, and no thunderstorms occurred. In eight of the remaining 19 cases, a trough or front was in the area, and the same reasoning applied that was used for the spring and fall incidents. However, the summer season differentiated from the other seasons in that 11 examples remained in which no troughs or fronts were within 200 km of either sounding location. In five of these cases, thunderstorms occurred. Therefore, another indictor had to be found to determine which answer the forecaster must choose.

After analysis of these 11 events, two factors were found to be good discriminators for thunderstorm/non-thunderstorm prediction. In several instances where no frontal boundaries were near the region, thunderstorms or outflow boundaries from thunderstorms west or northwest of the area advected into the region and triggered convection. Thus, thunderstorm activity within 200 km of the study area regardless of surface boundaries was used as an indicator of possible convection. In addition, one other factor was determined to be an indicator of thunderstorm generation. In most cases in which CAPE 2000 was less than 270 $m^2 s^{-2}$ in both soundings, no lightning was detected in the study area. In 27 of the 47 times when CAPE 2000 was greater than 270 $m^2 s^{-2}$ in one or both soundings, lightning was detected. In fact, CAPE 2000 seems to be a better indicator of non-thunderstorm periods than CAPE because it takes an average of the boundary layer moisture for its computation instead of an average of the lowest 500 meters, which tends to overestimate the low-level moisture condition.

Figure 55 is the decision method used for the summer season in forecasting thunderstorms at Whiteman AFB. The first steps, in which the two regression equations are evaluated and compared, are exactly the same as the decision model for the spring and fall seasons. If both equations are negative, no thunderstorms are predicted. If both equations are positive, thunderstorms should be expected. When one equation is positive and the other negative, however, the summer model differs from the other one. Step 5 asks if at least one sounding location has CAPE 2000 above 270 $m^2 s^{-2}$. If the answer is

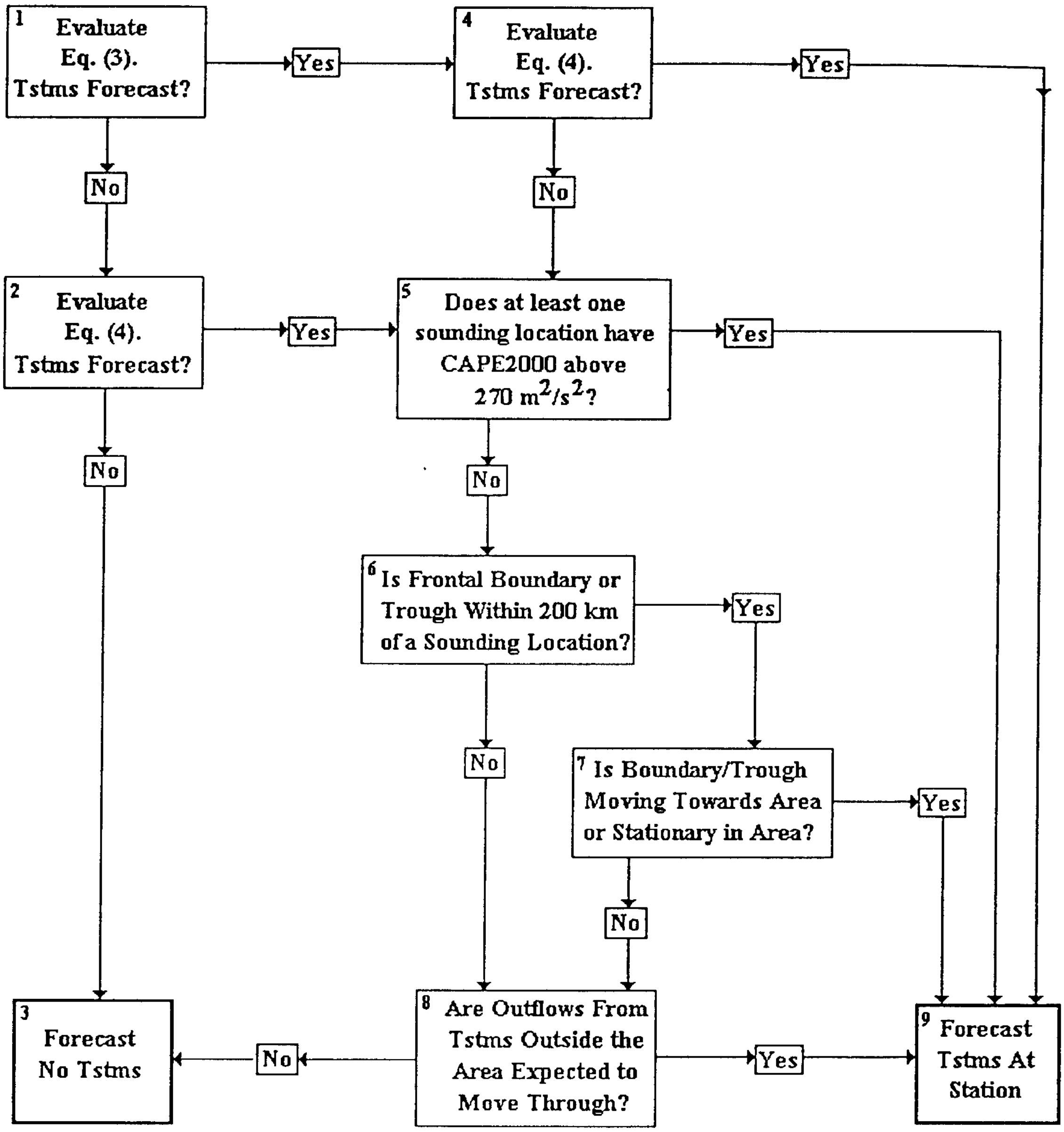

Figure 55. Thunderstorm decision model for the summer season at Whiteman Air Force Base. Abbreviations in the figure: Eq. - equation; Tstms - thunderstorms.

yes, the user is advised to forecast thunderstorms. For no answers, step 6 then asks if a frontal boundary or trough is within 200 km of a sounding location. Like the spring and fall model, a yes response directs the user to step 7, where they are asked to determine if the boundary is moving towards or is stationary over the area. If yes, a thunderstorm prediction is made. For negative responses to either step 6 or step 7, the forecaster is directed to step 8. This final decision step asks if thunderstorms or outflows from thunderstorms occurring outside the region are expected to move into the area during the forecast period. If the answer is again no, then thunderstorms are not forecast. A yes answer directs the user to predict thunderstorms.

The results of testing the 1995 summer data set with the summertime decision model are shown in Table 31. Thunderstorms were forecast to occur in 45 periods, in which 31 verified. In the other 32 cases in which thunderstorms were not forecast, only two periods did not verify. Although the model still tended to overestimate thunderstorm occurrence, improvement was seen over the results of each individual regression equation (see Tables 18 and 19). The CSI for the summer decision method was 66%, while POD was 94%, FAR was 31%, and YI was 0.62.

Table 31. Contingency table showing prediction results using the decision model in Figure 55 on the summer data set from 1995. TSTM stands for thunderstorm. The model correctly predicted 61 of 77 events.

	FORECAST TSTM	FORECAST NO TSTM	TOTAL
OBSERVED TSTM	31	2	33
OBSERVED NO TSTM	14	30	44
TOTAL	45	32	77

CHAPTER V
DISCUSSION AND CONCLUSIONS

1. Lightning summary

a. Number of flashes

From 1989 through 1995, 715 655 cloud-to-ground (CG) lightning flashes were detected in the study area by the National Lightning Detection Network (NLDN). Typically, the frequency of CG flashes increased from December to March, with a rapid increase through the spring before leveling off to a maximum in July. The number of flashes decreased slightly in August, then rapidly dropped in September through the fall to a yearly minimum in December. The tendency in the average number of positive polarity flashes per month was similar to that of the total flashes.

Overall, approximately 63% (450 767) of all CG flashes occurred in the summer months of June, July, and August. Only 0.4% (2672) of the total number of flashes were recorded in the winter months of December, January, and February, of which 1061 were recorded during one storm in February of 1995.

There was a large year-to-year difference in the number of CG flashes detected in the study area. The number of flashes ranged from 75 149 in 1989 to 174 447 in 1993, with an average per year of 102 251. However, 60% more flashes were recorded in 1993 than in any other year. With the exception of that year, the total flashes recorded each year were within one standard deviation of the mean. On the other hand, many more positive flashes were detected the last three years of the study compared to the first four. This was expected for 1993, since the total number of flashes was much greater than any other year. In contrast, 1994 and 1995 had nearly double the number of positive flashes as the first four years, despite comparable numbers of total flashes.

The percentage of positive lightning was highest in the winter, then declined during February and remained nearly stationary from March through May. Summer had the lowest percentage, with a yearly low found in August of 3.4%. Percentages increased slightly in September and October, then increased rapidly in November to the maximum once again in December and January. The monthly tendency in the percentage of positive

lightning for all months except December and January parallels Silver's (1995) findings for the entire United States. The higher percentages found in this study for those two months were due to the small sample size of data, and the fact that most of the winter activity for Silver's study is from the South and especially Florida, where the percentage of positive lightning is typically low (Orville, 1994).

The percentage of positive lightning for 1994 and 1995 was also twice that of previous years. A breakdown by month and season for each year showed that during the warm season, the percentages for both years were double those of the five previous years. Even so, the seven year average of 4.2% is very close to Reap and MacGorman's (1989) estimate that 4.33% of all warm season CG flashes for the central United States are positive.

The percentages for 1994 and 1995 were close to the other years from the middle of fall through early spring. However, the number and percentage of positive lightning were strongly influenced by individual storms, especially during the cool season when overall thunderstorm activity was infrequent. Single storms in March and November 1990 and February 1994 all dominated the percentages of positive lightning for those months.

The yearly number of thunderstorm days was notably consistent. Totals ranged from 93 days in 1989 to 114 in 1993, a 23% difference. A large day-to-day variability in the number of CG lightning flashes was apparent. About 100 000 more flashes were recorded in 1993 as compared to 1992, but in only six more thunderstorm days.

Thunderstorm days recorded at Whiteman Air Force Base (AFB) during March through November of 1993 and 1994 were approximately 50% fewer than for the study area. The nine month totals of 57 thunderstorm days in 1993 and 50 for 1994 compare favorably to the climatic average of 55 days for the same time period, even with regards to the excessive precipitation and lightning amounts reported for 1993.

Thunderstorm events were catalogued according to the total number of lightning flashes detected for each event. Only five of the 38 events which occurred in the winter were category 3 or 4 events. For the other nine months, 421 category 3 or 4 events were recorded over the seven year period, compared to 425 category 1 or 2 events.

From March through November of 1993 and 1994, weather observers at

Whiteman AFB reported thunderstorms 41% of the time that lightning was detected in the study region. Of the 47 category 1 events that occurred during this period, none were reported at Whiteman AFB. For category 2 events, only 11 of 75 (15%) were recorded at the base. However, 55% (32 of 58) of category 3 events and 90% (57 of 63) category 4 events were reported.

b. Peak current

First stroke peak currents were measured for both negative and positive flashes. For negative flashes, the winter months all show high mean peak currents over the seven year period with values between 39 kA (January) and 48 kA (December). The remainder of the year is uniform with mean peak currents averaging 35 kA in March and April to a yearly minimum of 32 kA in June. These values are very close to those found by Silver and Orville (1995) and Silver (1995).

Comparing the same months of different years revealed some variation. Yet, the lowest average peak current for six of the seven months from March through September were recorded in 1995. Values for August of 1995 were second lowest only to those of August 1991. All told, the spring mean peak current for 1995 of 28 kA was 6 kA lower than the seasonal average for the study area. The summer mean peak current of 26 kA was 7 kA lower than the seasonal average for the seven year period.

For positive flashes, maximum peak currents were also found in winter, with an 85 kA average for December. Peak currents declined until late spring, and remained nearly steady through the summer. Minimum value was 36 kA in August. Peak currents increased again during the fall. Once again, these results are similar to those of Silver and Orville (1995) and Silver (1995).

On a month-by-month basis, two different years stood out. Positive CG flashes in 1989 had continually high peak currents. The NLDN system, which was still in its early stages, was probably only recording flashes with high peak currents and missing those with lower currents. On the other hand, 1995 had steadily lower peak currents during the warm season. Positive flash peak currents for 1995 were 14 kA below normal for the spring season, and 8 kA below normal for the summer.

Both positive and negative flashes for each year were compared to determine how

many flashes between peak current increments were recorded on a yearly basis. The most flashes of lower peak currents for both kinds of flashes were detected in 1994 and 1995. Over 16 000 more negative flashes below 20 kA were recorded in 1995 than in any other year except 1994. This amount was nearly double the total for any other year. However, no increase was seen on a year-to-year basis in the number of flashes greater than 20 kA. The cumulative percentage of negative flashes showed that about 15% of all flashes recorded from 1989 through 1993 had peak currents below 20 kA. For 1994 and 1995, about 35% of all negative flashes recorded had peak currents below 20 kA.

For positive flashes, more than half of all flashes with peak currents less than 30 kA during the seven year period were reported in 1994 and 1995. Increases in the number of flashes detected with peak currents between 30-60 kA during the last two years were also noticed. The cumulative percentage of positive flashes showed that about 50% of all positive flashes recorded from 1989 through 1993 were below 40 kA. For 1994 and 1995, this percentage was more than 60%.

Large increases were seen in 1994 and 1995 over previous years, both in the number of negative and positive flashes detected at lower peak currents, and in the percentage of positive lightning. Cummins et al. (1995) claim that increase in the gain in the existing magnetic detection finders and the integration of the time-of-arrival system into the NLDN improved the detection efficiency. The increases discovered in this study strongly suggest that this is the case for positive flashes. Furthermore, there was a question of whether the "improved" NLDN was detecting intracloud flashes instead of positive CG lightning flashes of lower peak current or both (Richard Orville, personal communication, 1996). If the system is detecting intracloud flashes, the increase in percent positive should be seen throughout the year. Since the increase was only been seen during the warm season, when positive peak currents are typically lower, the NLDN would seem to be detecting positive flashes. However, since the increase in the number of negative flashes was only observed below 20 kA, the possibility that intracloud flashes are being recorded by the network still exists. More detailed studies need to be accomplished to prove that the detection efficiency has indeed improved, and that the system is not detecting intracloud flashes.

c. Diurnal tendencies

The diurnal distribution of CG lightning indicated a minimum in activity between 1500-1600 UTC (0900-1000 CST). The peak in activity was at 2200 UTC, with a secondary maximum at 0500 UTC. This tendency was observed in both the spring and summer periods. The late morning minimum and late afternoon peak during the summer season are similar to those found by Reap and MacGorman (1989). However, they did not see the peak in activity around midnight local time found in this study.

For the fall season, a maximum in activity occurred at 0000 UTC, and declined slowly and erratically to a minimum at 1800 UTC. The most notable feature in the fall is the disappearance of the overnight maximum seen during the spring and summer seasons.

The first flash of lightning, signaling the beginning of thunderstorm activity, was possible at any time of day. These findings agree with those of Easterling and Robinson (1985), who find that in the central United States, the most storms occur at night, but are frequent any time. When only category 3 and 4 events were examined, the preferred time of first flash was more pronounced at 1800-2100 UTC, with a minimum time between 1200-1500 UTC. Seasonally, first flash times for spring were spread evenly, except for a distinct minimum from 0900-1500 UTC. First flashes for summer were spread evenly as well, except for a large maximum between 1800-2100 UTC. On the other hand, several peaks were found during the fall, from 1800-2400 UTC and 0600-0900 UTC.

The last flash occurred at all times of the day as well, but a small preference was found for the late afternoon and early evening (2100-0300 UTC), and the early morning (1200-1500 UTC). Favored last flash times for category 3 and 4 events followed these trends as well.

The diurnal tendencies of lightning flashes in the study area suggest that spring and fall thunderstorms are normally associated with some type of frontal boundary. Therefore, the timing of the front through the region is an important factor in the timing of thunderstorm activity. For thunderstorms during the summer, the late afternoon peak in first flash times indicate that afternoon heating is the initial trigger for convection. The small peak in last flash times in the early evening, and the decrease in lightning activity, suggest that as afternoon heating disappears, the atmosphere starts to become more stable

and thunderstorms frequently die out. However, if a disturbance such as a front or trough is near the region, MCSs or MCCs generated by the boundary may advect into the area during the evening. This would justify why the peak lightning activity at 0600 UTC is about 3 hours later than that found by Reap and MacGorman (1989). The high flash rates of MCSs and MCCs (Goodman and MacGorman, 1986) would explain the peak in nocturnal flash amounts found in Figure 13. With an average duration in the study area of 9.7 hours between first and last flash of category 3 and 4 events during the summer, this would account for the early morning peak in last flash times.

A diurnal pattern was evident for positive flashes as well. The pattern was very similar in shape to the trend for total flashes, with a lag behind the total flash tendency of 1-2 hours. This lag was observed throughout the three seasons. The summertime minimum in positive flashes between 1500-1800 UTC (0900-1200 local time) matches the minimum found by Reap and MacGorman (1989), but the peak at 0600 UTC is about three hours later than what they found.

The time of sharpest decline in activity after the peak in positive flashes for each season coincided with the time of the largest number of last flash events for that respective season. The lag in peak times between total and positive flashes, and the correlation of time of decline in positive flashes to the time of maximum last flash events, demonstrates that the highest amount of positive lightning is located in the stratiform region of thunderstorms.

d. Spatial distributions

Ground flash densities (GFD) were described on both a seasonal and yearly basis for all CG lightning flashes and for positive flashes only. Values for positive lightning were much lower than for the total number of flashes, and therefore easily influenced by individual storm systems containing high amounts of positive lightning.

The year-to-year GFD patterns showed large variability. Ground flash density contours were constructed for 1990. Maximum value was 9.0 flashes km^{-2}, located approximately 50 km south-southwest of Whiteman AFB. For the entire region, values ranged from 2.5-9.0 flashes km^{-2}. These values were typical of all years except 1993. For 1993, a maximum of 19 flashes km^{-2} was observed approximately 70 km east-northeast of

Kansas City. This maximum was up to four times higher than the GFD values found in the southern half of the study area for the same year. Furthermore, the area of minimum flash density for 1993 was the same location that recorded the maximum value in 1990.

No preferred locations of maxima or minima were found in the year-to-year GFD patterns. Terrain elevations in the study area generally range from 210-350 meters above sea level, with uneven topography. In agreement with Lopez and Holle (1986) and Reap and MacGorman (1989), these small differences in terrain did not seem to influence spatial distributions of lightning frequencies.

The average yearly GFD pattern showed a maximum value of 6.4-7.8 flashes km^{-2} was located north of Whiteman AFB and just east-northeast of Kansas City. Several areas of minimum GFD values of 3.6-5.0 flashes km^{-2} were evident, with the largest areas near the southeast corner of the region and also just south of Kansas City.

For positive flashes over the total period, the maximum area of GFD values were located in the southern half of the box. Since the area of maximum GFD for total flashes was found in the northern half, this would seem to be an apparent contradiction to the bipolar patterns found by Orville et al. (1988), Engholm et al. (1990), and Stolzenburg (1990). Yet, it is possible that the area of higher positive flash densities may correspond to an unseen maximum area for total flashes located to the southwest of the study region. Similarly, an area of higher positive flash densities associated with the maximum area of GFD for all flashes in the study region may possibly be located north and out of the region. Thus these findings are inconclusive for bipolar lightning patterns.

An analysis of all thunderstorm events during the spring which produced at least 5000 flashes was performed. The nine events compiled combined to produce 43% of the total flashes measured over the entire seven spring seasons. Ground flash density plots of these nine events showed significantly higher GFD values located to the south-southeast of Whiteman AFB, with lower values located in the northern part of the box. These results exhibited a definite preferred path for high CG lightning flash storm during the spring. As stated earlier, terrain variations in the study area do no seem to influence spatial distributions of lightning frequencies on a yearly basis. However, the Ozark mountains are located just to the south of this region. One hypothesis for this preferred

path of springtime activity is that surface convergence may be slightly enhanced in this area by the Ozarks, similar to what Lopez and Holle (1986) found in northeast Colorado. Unfortunately, no evidence of a preferred track of storms was found for the summer or fall periods. Further study is needed on this issue to determine the cause of this effect.

For the summer period, the northern one-third of the region averaged 3.9-6.3 flashes km^{-2}, while most of the remaining area averaged 2.5-3.9 flashes km^{-2}. Because 1993 had nearly twice as many flashes as any other year, flashes from this year were extracted and the summertime GFD plot redone using the remaining data. The overall pattern of GFD for the new plot was much smoother than the original summer chart. A small maximum was still located near the northern end of the region, but was much smaller than when 1993 data was included. The new GFD plot clearly showed how 1993 activity influenced the contours for the summer period.

Contrary to Westcott's (1995) finding, higher CG lightning frequencies were not observed downwind of the Kansas City area. Although pockets of higher GFD values were observed in the average summer period northeast of Kansas City, high variability from summer-to-summer precluded seeing a consistent pattern that would suggest an urban heat island effect. However, this study was not done on the smaller spatial scale used by Westcott, or on an individual storm basis.

2. Thunderstorm prediction model

a. Stability index and thermodynamic variable correlations

Linear correlation coefficients relating lightning activity in the study area to 12 indices and variables from two rawinsonde locations were found for the spring, summer, and fall seasons.

Indices from Monett soundings that had the best correlations during the spring were Showalter stability index (SSI) (-0.61) and lifted index (LI) (-0.59). For the summer, LI and the severe weather threat index (SWEAT) had the highest correlations of -0.36 and 0.27 respectively. These two indices also had the highest correlations for fall, with a coefficient of -0.55 for LI and 0.54 for SWEAT.

For indices from Topeka soundings, SSI had the highest correlation during the spring of -0.49, followed by LI at -0.46. The K index (KI) (0.38) and SSI (-0.29) were

highest during the summer season. These same indices had the highest correlations for the fall as well, at 0.60 (KI) and -0.59 (SSI).

Correlations for all variables at both sounding locations were higher in the spring and fall than in the summer. The spring and fall correlation coefficients for SSI, LI, and KI are about the same or slightly lower than those found by Stone (1985) and Livingston (1995). Stone's correlation coefficients are -0.64 for LI, -0.61 for SSI, and 0.54 for KI. Livingston's values are -0.60 (SSI), 0.56 (KI), and -0.52 (LI). In addition, their coefficients are much higher than those found for the summer period in this study.

Since only 9% of category 1 and 2 events were reported at the base during this period, correlations of indices were computed comparing non-thunderstorm periods to category 3 and 4 events only. Coefficients were about 0.06 higher per index per season at Monett than for all thunderstorm days versus non-thunderstorm days, and over 0.03 higher at Topeka.

Statistical difference in the values of sounding variables between non-thunderstorm periods and category 3 and 4 thunderstorm periods in the study area were analyzed by rawinsonde location on a seasonal basis. A large difference in the medians and means was apparent for every variable at both locations during the spring and fall. For example, the median of SSI from Monett soundings for non-thunderstorm periods in spring was +8.73 (See Table 11). For thunderstorm periods, the median was -0.93. The median of KI for non-thunderstorm periods was 6.7, but was 31.0 for thunderstorm periods. Similar results are found in Table 13.

Differences in medians and means during the summer season were not as large. The median of SSI from Monett soundings for non-thunderstorm periods in the summer was +0.52, compared to -1.82 for category 3 and 4 periods. The median of KI was 26.1 for non-thunderstorm times, and 32.6 for thunderstorm periods (See Table 12).

Examination of the data for all seasons showed a large difference in values of indices for non-thunderstorm days between summer and the other seasons. Conversely, a small difference was observed in values for thunderstorm periods of different seasons.

b. Regression analyses

Linear regression equations were developed from the seasonal data sets obtained

from Monett and Topeka for March through November of 1993 and 1994. A total of six equations were developed, one for each season and location. These equations were used to differentiate thunderstorm periods from non-thunderstorm periods. A negative response was a prediction of no thunderstorms for the 13 hour period after the sounding time. A positive response was a prediction of thunderstorm occurrence in the study area within the 13 hour period after the valid sounding time. Equations were tested against the data set from that particular season, and against an independent data set of 1995 soundings from that location. Skill scores used to test the accuracy of each equations were the critical success index (CSI), false alarm rate (FAR), probability of detection (POD), and Yule's index (YI). A summary and equations for these scores are in the Appendix.

For the six different equations, combinations of only four indices are used. These indices are SSI, KI, LI, and SWEAT. All equations use three of the four indices except equation (4), which uses only two.

For the spring season, equation (1) performed slightly better than equation (2) when tested on the independent data set. Overall, equation (1) predicted the correct outcome 88% of the time, while equation (2) predicted the right occurrence 87% of the time. The CSI for equation (1) was 59% , while the POD was 87%, the FAR was 35%, and YI was 0.68. For equation (2), CSI was 55%, POD was 80%, FAR was 37%, and YI was 0.63.

The equations for the summer season did not perform as well as those for spring. Equation (3) predicted the correct outcome 70% of the time for the independent data set, while equation (4) was right 73% of the time. The CSI scores of 55% for equation (3) and 58% for equation (4) were artificially high due to the correct prediction of many thunderstorm events. Both equations, however, tended to over predict thunderstorm occurrences, with a FAR of 39% and 36% for equations (3) and (4), respectively. Yule's index, which takes into account the overall prediction of both thunderstorm and non-thunderstorm periods, gave a better indication of the total accuracy of the models with a score of 0.44 for equation (3) and 0.51 for equation (4). The CSI for equation (3) of 55% was still better than the 43% scored by Livingston's (1995) regression model of inactive

lightning days versus all other days for 1994 data. The FAR of 39% for equation (3) is better than his FAR of 55%, while the POD of 85% is comparable to his POD of 88%.

For the fall season, equation (5) predicted the outcome correctly 83% of the time. Equation (6) was correct 84% of the time. The skill scores were lower than for the spring, but better than those for the summer. Equation (5) had a CSI of 50%, a POD of 83%, a FAR of 44%, and a YI of 0.58. Finally, equation (6) had a CSI of 50%, a POD of 75%, a FAR of 40%, and a YI of 0.57.

c. Decision method

The responses of the two equations for the same time period of each season were compared to examine similarities and differences. If both equations gave positive responses, thunderstorms were predicted. If both equations gave negative answers, no thunderstorms were predicted. For the independent data set from 1995, 214 sample periods were examined. Cloud-to-ground lightning flashes occurred in the study area during 60 of these periods. There were no cases in which both equations gave negative responses for a thunderstorm period. In 41 of the cases, both equations gave positive responses. For the other 19, one equation gave a positive response, while the other gave a negative response. Similarly, for the remaining 154 non-thunderstorm periods, both equations gave negative responses 107 times. False alarms (both equations positive) were recorded 18 times, and the equations differed from each other 29 times.

In the cases for which the equations differed, a method was determined to decide which response was correct. During the spring and fall, the determining factor was the presence of a frontal boundary or trough within 200 km of either rawinsonde location. The final decision depended on whether the boundary was moving towards the study area, or was stationary in the area.

Using these factors, the decision model found in Figure 54 was formulated. The user is asked to evaluate and compare equation responses. If both are positive, thunderstorms are predicted sometime within the 13 hours after the sounding time. If both responses are negative, thunderstorms are not predicted during that period. If the responses differ, the forecaster is asked to check for frontal boundaries or troughs in the area and their general movement. This task can be accomplished using the most recent

surface analysis chart. The forecaster simply follows the decision sequence associated with their answer to those questions.

This decision model was tested on the independent data set for spring. All 15 thunderstorm events were correctly forecast, with only four false alarms. Skill scores were: CSI of 79%, POD of 100%, FAR of 21%, and YI of 0.86. For the fall, 11 of 12 thunderstorm events were correctly predicted, with six false alarms. This produced a CSI of 61%, a FAR of 35%, POD of 92%, and a YI of 0.70. The decision model showed improvement over all four individual regression equations.

For the summer, similar factors were considered. However, the lack of a frontal boundary or trough did not rule out thunderstorms in the study area. A good discriminator was found by using the median value of CAPE 2000 from Table 12. Also, several instances were found in which thunderstorms occurred due to thunderstorms or their outflows outside of the region advecting into the area. These two factors were included in the decision model for summer seen in Figure 55.

The model begins the same way as the previous model. If equation responses differ, the forecaster is asked to compare sounding values of CAPE 2000 from both locations. If either sounding has a CAPE 2000 above 270 $m^2 s^{-2}$, thunderstorms are forecast. A no response does not rule out thunderstorms, however. The forecaster is then asked about frontal boundaries or troughs. The same methods are applied as with the first decision model. Yes responses again lead to the forecast of thunderstorms. No responses lead to the last decision square on whether thunderstorms or outflows from outside the area are expected to move in. Once again, a yes answer leads to thunderstorm prediction, while a no response finally leads to a forecast of no thunderstorms.

Skill scores from the test of the summer decision model showed a CSI of 66%, a POD of 94%, a FAR of 31%, and a YI of 0.62. Although the model still tends to overestimate thunderstorm occurrence, improvement is seen over the results of each individual regression equation. These skill scores were also significantly better than those from Lee and Passner's (1993) expert system, which has a CSI of 50% and a FAR of 41% for thunderstorm occurrence within a 100 km radius around Topeka.

Finally, although promising results were obtained from both decision models, more testing is needed on each model. An operational test performed at Whiteman AFB on a day-to-day basis would be the best scenario. An accumulation of several years worth of results could then be used to refine the indices used in both the decision models and in the regression equations. Furthermore, it must be cautioned that if time permits, the results from the model should be used in conjunction with computer forecast products, not instead of them.

3. Summary

A lightning summary of the region around Whiteman AFB created from a data base of cloud-to-ground lightning flashes detected in the area from 1989 through 1995 showed that a preferred track for large spring thunderstorms exists just to the south of the base. No preferred track was found for summer or fall convection.

The number of lightning flashes detected in the study area in 1993 was 60% higher than for any other year. Furthermore, flash densities of up to 19 flashes km^{-2} were observed in the northern third of the box, almost three times the highest yearly average ground flash density.

Neither a bipolar pattern of CG lightning nor an increase in lightning activity downwind of a major urban area (Kansas City) were found in this study. However, different spatial scales from those used in other studies and the size of the study region in general precluded making a judgment on the validity of those occurrences.

Diurnal distributions of lightning flashes showed that thunderstorms were possible during any time of day. But, both a late afternoon and a distinct nocturnal maximum in lightning frequency was observed during the spring and summer seasons. The nocturnal maximum disappeared during the fall season. A large difference in the medians and means was apparent for every stability and thermodynamic variable derived from Topeka and Monett soundings during the spring and fall, but not as large during the summer. Examination of the data for all seasons showed a large difference in values of indices for non-thunderstorm days between summer and the other seasons. Little difference was observed in values for thunderstorm periods regardless of the season. Spring and fall season thunderstorms were found to be dependent on frontal activity in the region.

Summertime thunderstorms could be triggered by other factors such as afternoon heating but were affected by boundaries which helped to sustain activity.

A definite increase in the percentage of positive lightning was discovered during the warm seasons of both 1994 and 1995. This coincided with a large increase in the number of both positive and negative flashes with lower peak currents being detected in 1994 and 1995 than in the previous five years. These results strongly suggest that the detection efficiency of the NLDN for positive flashes increased when the gain was increased and the TOA system was integrated in 1994. Results were inconclusive on whether detection efficiency for negative flashes increased.

Highest correlation coefficients for variables derived from Monett sounding were for SSI (-0.61) in the spring, LI (-0.36) in the summer, and LI (-0.55) in the fall. For Topeka, highest coefficients were for SSI (-0.49) in the spring, KI (0.38) in the summer, and KI (0.60) in the fall.

Six regression equations were developed to predict thunderstorm occurrence using stability indices. Skill scores showed that the equations for the spring and fall seasons performed better than those for the summer season. The responses of two equations from the same season for the same time period were compared. Of the 60 thunderstorm periods sampled, in no instance did both equations predict a non-thunderstorm occurrence. Two positive responses were given for a non-thunderstorm occurrence 18 times out of 154 chances (12%). For 48 of the 214 cases (22%), one equation gave a positive response while the other gave a negative response.

Simple decision models were constructed using the two regression equations for each season and other important factors such as frontal location and movement. One model was made for the spring and fall, while a slightly different model was made for the summer. The same independent data used to test the regression equations was used to test the models. Skill scores for the models over all three seasons were better than those for any one individual regression equation. However, more tests need to be performed on these models to examine their effectiveness during day-to-day operations.

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APPENDIX

DEFINITIONS AND FORMULAS FOR SKILL INDICES, STABILITY INDICES, AND THERMODYNAMIC VARIABLES

Convective Available Potential Energy (CAPE) - Measure of the work done on a parcel of air by the environment as the parcel is accelerated upward. CAPE represents the area on a thermodynamic diagram enclosed by the environmental temperature profile and the moist adiabat connecting the level of free convection (LFC) to the equilibrium level (EL).

$CAPE = \int g \frac{T_v(z) - T^*_v(z)}{T^*_v(z)} dz$, with EL and LFC the upper and lower limits, respectively.

g = acceleration due to gravity

$T_v(z)$ = virtual temperature profile of an air parcel ascending moist adiabatically from the LFC.

$T^*_v(z)$ = virtual temperature profile of the environment.

For CAPE, the LFC is determined using surface values of temperature and dewpoint.

For CAPE 1000, the LFC is determined by using the average temperature and average dewpoint for the lowest 1000 meters of the atmosphere.

For CAPE 2000, the LFC is determined by using the average temperature and average dewpoint for the lowest 2000 meters of the atmosphere.

Cross Totals (CT) - Measure of stability by comparing temperature in degrees Celsius at 850 mb with temperature in degrees Celsius at 500 mb.

$CT = T_{850} - T_{500}$

T = Temperature in degrees Celsius.

Subscripts indicate pressure level in millibars.

Equilibrium Level (EL) - Level at which the temperature of a parcel lifted above the LFC and the temperature of the environment again become equal.

Equivalent potential temperature (Theta-e) - The potential temperature that corresponds to the temperature that an air parcel would have after rising dry-adiabatically until

saturated; pseudo-adiabatically until all moisture is precipitated out; and then dry-adiabatic compression back down to the initial level.

$$Theta - e = \vartheta_{LCL} \exp\left(\frac{L_v\ r_s}{C_{pd}\, T_{LCL}}\right)$$

ϑ_{LCL} = Potential temperature of LCL in degrees kelvins.

L_v = Latent heat of vaporization in J g^{-1}.

r_s = Saturation water-vapor mixing ratio in g kg^{-1}.

C_{pd} = Specific heat at constant pressure of dry air (1004 J k^{-1} kg^{-1})

T_{LCL} = Temperature at LCL in degrees kelvins.

K index (KI) - Index which provides an indication of potential instability in the lower half of the atmosphere, availability of moisture in the boundary layer, and reduction of buoyancy through entrainment of dry air.

$KI = (T_{850} - T_{500}) + TD_{850} - (T_{700} - TD_{700})$

T = Temperature in Celsius.

TD = Dewpoint in Celsius.

Subscripts indicate pressure level in millibars.

Level of free convection (LFC) - The level at which a parcel of air lifted dry-adiabatically until saturated and saturation-adiabatically thereafter would first become warmer than the corresponding environment in a conditionally unstable atmosphere.

Lifted condensation level (LCL) - Level at which a parcel of air lifted dry-adiabatically becomes saturated.

Lifted index (LI) - Index that measures the temperature excess at 500 mb of the environment with respect to an air parcel in the boundary layer that is lifted to its LCL, and then lifted moist-adiabatically from the LCL to 500 mb. Surface temperature and dewpoint or an average temperature and average dewpoint of the boundary layer may be used.

$LI = T_{500} - T_p$

T_{500} = Temperature in degrees Celsius of the environment at 500 mb.

Tp = Temperature of an air parcel in degrees Celsius after it has been lifted from the boundary layer to 500 mb.

Severe Weather Threat index (SWEAT) - Index used initially as a method to predict severe thunderstorms by taking into account low-level moisture, low- to mid-level temperatures, and wind speed and direction at different levels.

SWEAT = $12(D_{850}) + 20\,(TT - 49) + 2(f_{850}) + f_{500} + 125(S + .2)$

D = Dewpoint in degrees Celsius (set to 0 if dewpoint is negative).

TT = Total Totals in degrees Celsius (set to 0 if TT is less than 49).

f = speed of wind in knots.

S = Sine of 500 mb - 850 mb wind direction.

Subscripts indicate pressure level in millibars.

Entire term 125(S + .2) is set to zero if any of the following conditions are not met: 850 mb wind direction in the range 130 through 250 degrees; 500 mb wind direction in the range 210 through 310 degrees; 500 mb wind direction - 850 mb wind direction positive; and both 850 mb and 500 mb wind speeds at least 15 knots.

Skill index - Indices used to determine skill scores for yes/no prediction of an event, based on a 2 x 2 contingency table of forecast versus observed states (Table 32).

Table 32. A 2 x 2 contingency table of forecast versus observed states, used to determine skill scores for yes/no prediction of an event.

	FORECAST EVENT	FORECAST NO EVENT	TOTAL
OBSERVED EVENT	a	b	(a+b)
OBSERVED NO EVENT	c	d	(c+d)
TOTAL	(a+c)	(b+d)	(a+b+c+d)

Equations for the indices are:

Critical Success Index - $CSI = \dfrac{100a}{(a+b+c)}$

False Alarm Rate - $FAR = \dfrac{100c}{(a+c)}$

Probability of Detection - $POD = \frac{100a}{(a+b)}$

Yule's Index - $YI = \frac{(ad - bc)}{[(a+b)(a+c)(c+d)(b+d)]^{1/2}}$

If "occurrence" is denoted by +1 and "non-occurrence" by 0, YI is the correlation coefficient between forecast and observed events. CSI and POD are similar, except the range is 0% for all misses to 100% for a perfect score. FAR is opposite in that 0% is perfect and 100% is always wrong.

Showalter stability index (SSI) - Indication of the local static stability of the atmosphere by comparing the temperature of the environment at 500 mb to an air parcel initially at 850 mb that is lifted to its LCL and then moist-adiabatically to 500 mb.

$SSI = T_{500} - T_p$

T_{500} = Temperature in degrees Celsius of the environment at 500 mb.

T_p = Temperature in degrees Celsius at 500 mb of a parcel initially lifted from 850 mb.

Total Totals (TT) - Combination of cross totals and vertical totals. Measures the stability by comparing temperature and dewpoint at 850 mb with the temperature at 500 mb.

$TT = T_{850} + D_{850} - 2(T_{500})$

T = Temperature in degrees Celsius.

D = Dewpoint in degrees Celsius.

Subscripts indicate pressure level in millibars.

Vertical Totals (VT) - Measure of stability by comparing dewpoint at 850 mb with the temperature at 500 mb.

$VT = D_{850} - T_{500}$

D_{850} = Dewpoint in degrees Celsius of the environment at 850 mb.

T_{500} = Temperature in degrees Celsius of the environment at 500 mb.

VITA

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Randall lives with his wife Amy and daughter Briana. [redacted].